Court of Appeal File No. C65807

COURT OF APPEAL FOR ONTARIO

IN THE MATTER OF A REFERENCE to the Court of Appeal pursuant to section 8 of the *Courts of Justice Act*, RSO 1990, c. C. 34, by Order-in-Council 1014/2018 respecting the constitutionality of the *Greenhouse Gas Pollution Pricing Act*, Part 5 of the *Budget Implementation Act*, *No. 1,* SC 2018, c. 12

RECORD OF THE INTERVENOR, THE ATTORNEY GENERAL OF BRITISH COLUMBIA

(Reference returnable April 15-18, 2019)

February 22, 2019

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Court of Appeal File No. C65807

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T. Lesiuk Affidavit #2
January , 2019
Court of Appeal File No. C65807

COURT OF APPEAL FOR ONTARIO

IN THE MATTER OF A REFERENCE to the Court of Appeal pursuant to section 8 of the *Courts of Justice Act*, RSO 1990, c. C. 34, by Order-in-Council 1014/2018 respecting the constitutionality of the *Greenhouse Gas Pollution Pricing Act*, Part 5 of the *Budget Implementation Act, No. 1,* SC 2018, c. 12

AFFIDAVIT

I, Tim Lesiuk, of 525 Superior Street, Victoria, BC, Executive Director, Clean Growth Strategy, Climate Action Secretariat, Ministry of Environment and Climate Change Strategy SWEAR THAT:

1. I am the Executive Director for Clean Growth Strategy in the Climate Action Secretariat for British Columbia's Ministry of Environment and Climate Change Strategy. My curriculum vitae is attached as **Exhibit A**.

2. The Climate Action Secretariat acts as the point of coordination for information from across the British Columbia provincial government in relation to climate policy. The Secretariat provides support to the Climate Solutions and Clean Growth Advisory Council, a consultative advisory group to government consisting of representatives of Indigenous governments, environmental organizations, industry, academia, labour and local government.

Climate Change in British Columbia

3. On June 16, 2016, the Ministry published the 2016 Update to "Indicators of Climate Change for British Columbia", the first version of which was published in 2002. This Indicators Report presents trends in the climate of BC based on a set of environmental indicators that represent key properties of the climate system, or important ecological, social, or economic values that are considered sensitive to climate

change. The report describes changes in these indicators over time. Past trends are based on analysis of historical data. A copy of the report is attached as **Exhibit B** to this affidavit.

4. The Indicators Report presents only those results within a "95% confidence interval." That means that it only reports a trend if there is a less than one-in-twenty chance the data that are the basis of the trend could have arisen randomly.

5. Analysis of historical data indicates that many properties of climate have changed during the 20th and early 21st centuries, affecting marine, freshwater, and terrestrial ecosystems in British Columbia.

a. Average annual temperature warmed by 1.4°C per century across the province. This compares to a global warming of around 1 °C.

b. The northern regions of BC warmed more than the provincial average.

c. Night-time temperatures increased across all of BC in all seasons.

d. The night-time minimum average temperature in winter in BC increased by 3.1°C per century.

e. Annual precipitation has been increasing across the province overall.

f. Lakes and rivers become free of ice earlier in the spring.

g. The bulk of river flow is occurring earlier in the year.

h. Average sea level has risen along most of the BC coast.

i. Sea surface temperatures have increased along the BC coast.

j. Water in the Fraser River is warmer in summer.

k. More heat energy is available for plant and insect growth.

6. Climate models and scenarios suggest that the climate in British Columbia will continue to change throughout and beyond the 21st century. This will have ongoing impacts on ecosystems and communities. According to the Indicators Report, some of the impacts British Columbia may experience by the end of the 21st century include

a. Average annual temperature in BC may increase by 1.7°C to 4.5°C from 1961-1990 temperatures.

b. Average annual precipitation may increase by 4 to 17 percent from 1961-1990 levels.

c. Most small glaciers in southern BC will likely disappear.

d. Some of the smaller rivers in southern BC may dry up during the summer and early fall.

e. Salmon migration patterns and success in spawning are likely to change.

Mountain Pine Beetle

7. Already in the 2002 version of the Indicators report, it was identified that warmer winters expanded the range of the mountain pine beetle in British Columbia. The beetle attacks western pines, particularly the lodgepole pines. While the beetle has always been endemic to British Columbia's pine forests, its range was historically controlled by low temperatures in winter. With climate change, its range expanded in an epidemic outbreak in the 1990s and 2000s in British Columbia. According to a National Resources Canada web factsheet, attached as **Exhibit C** to this affidavit, over 18 million hectares of forest were impacted to some degree, resulting in a loss of approximately 723 million cubic metres (53%) of the merchantable pine volume by 2012. The epidemic peaked in 2005: total cumulative losses from the outbreak are projected to be 752 million cubic metres (58%).

Wildfire Risks

8. The Indicators Report shows summers have become longer and dryer, and states that reduced moisture in summer may contribute to forest fires. This is consistent

with the difference in fire seasons in British Columbia and more southern latitudes such as California. 2017 and 2018 were the most expensive fire seasons in British Columbia's history. According to a 2017 article in *Climate Change,* attached as **Exhibit D** to this affidavit, human greenhouse gas emissions have already made extreme fire events 1.5 to 6 times more likely than they would have been based on natural forcings alone.

Sea Level Rise

9. A 2014 Report by Natural Resources Canada (NRCAN) edited by F.J. Warren and D.S. Lemmen, entitled "CANADA IN A CHANGING CLIMATE: Sector Perspectives on Impacts and Adaptation" has a discussion of sea level rises caused by global climate change in Canada. A copy of Part 5.4 of Chapter 2 entitled "Sea Level Change" is attached as **Exhibit E** to this affidavit.

10. In the 20th and early 21st century (1909 to 2006), sea level rose at an average rate of 0.6 mm/yr in Vancouver and Victoria, and 1.3 mm/yr in Prince Rupert, and fell by 0.9 mm/yr in Tofino. The NRCAN Report states a range of 55 to 115 cm of global sea-level rise by 2100 has been derived for use in flood risk planning. Coastal British Columbia will be more affected than other parts of Canada because of the relative unimportance of compensating melt-water redistribution and geological change. In addition to higher average levels, global climate change will increase extreme flooding events .British Columbia does not currently have a rigorous estimate of the amount of economic damage a rise of this level would cause.

Melting of Permafrost

11. As the Indicators report states, temperature increase has been more rapid in northern and high altitude British Columbia than elsewhere. This poses increasing risks of melting of permafrost. As an example of the new challenges that this will pose, I attach as **Exhibit F** to this affidavit a January 18, 2018 announcement by the Lil'wat Nation, Squamish-Lillooet Regional District and Village of Pemeberton of a risk assessment of landslide risk for Mount Currie. It discloses that loss of permafrost will increase risk of landslide and recommends continuing monitoring at this time.

12. This is one example. We do not yet have a comprehensive inventory of the economic and other challenges of melting permafrost for British Columbia's communities. According to the NRCAN Report referred to in paragraph 9, northern transportation infrastructure is seriously imperiled by loss of permafrost and shorter ice road seasons, and these will affect northern British Columbia as well.

Ocean Acidification

13. Increases in ocean temperatures and carbon dioxide concentrations in the ocean change the pH balance (acidity) of the ocean. Scientists estimate that the ocean has become 0.1 pH unit more acidic since pre-industrial times or a 26% increase in acidity. This inhibits the ability of marine life to form shells and has other detrimental effects. A 2015 Research Article published in pLOS by Rowan Haigh, Debby Ianson, Carrie A. Holt, Holly E. Neate and Andrew M. Edwards entitled "Effects of Ocean Acidification on Temperate Coastal Marine Ecosystems and Fisheries in the Northeast Pacific" surveys current knowledge about the impacts of ocean acidification on commercial and sports fisheries in British Columbia. A copy of the article by Haigh and his co-authors is attached as **Exhibit G.**

14. Haigh et al. make the following conclusions in order of immediacy and certainty:

a. Shellfish aquaculture is highly susceptible to ocean acidification (OA) due to the direct impact of OA on shell formation and the dependence of the industry on hatchery production.

b. There are no studies on Geoduck Clams, which are responsible for a lucrative wild fishery and a growing aquaculture industry in BC.

c. The commercial BC fishery is dominated monetarily by salmon aquaculture. While uncertainty remains low, it is anticipated that the fish-killing alga *Heterosigma akashiwo* will gain a competitive advantage under OA, making blooms more frequent. Such blooms are already a significant issue for this industry in BC.

d. Neurotoxins produced by other harmful algae are expected to become more potent under OA. Such blooms already cause shellfish closures in BC. If this increase in toxicity occurs, the shellfish industry will be affected. In addition, these toxins may cause decreased reproductive success, and even mass mortality, at higher trophic levels including fish, seabirds and marine mammals.

e. Food web changes due to OA are anticipated but remain unknown, as are the impacts of these lower level changes higher up the food chain. Finfish are likely to experience OA impacts through food web changes. Habitat changes may also have a critical negative impact, in particular for juvenile finfish. Direct impacts of OA on finfish may also occur, but only at relatively high levels of CO2.

f. The impacts on economically-significant speices such as halibut and salmon have not been studied. Because sport fishing dominates fishery related income in BC, this knowledge gap is significant.

The Impact of Less Snow and More Rain on Hydroelectric Generation

15. In 2012, British Columbia Hydro and Power Authority published "Potential Impacts of Climate Change on BC Hydro's Water Resources.| This Water Resources Report summarizes BC Hydro's work with world's leading scientists in climatology, glaciology, and hydrology to determine how climate change affects water supply and the seasonal timing of reservoir inflows, and what we can expect in the future. A copy of the Water Resources Report is attached as **Exhibit H** to this affidavit.

16. According to the Water Resources Report, over the last century, the following occurred:

a. All regions of British Columbia became warmer by an average of about 1.2°C.

b. Annual precipitation in British Columbia increased by about 20 per cent.

c. Fall and winter inflows have shown an increase in almost all regions, and there is weaker evidence for a modest decline in late-summer flows for those basins driven primarily by melt of glacial ice and/or seasonal snowpack.

17. The Water Resources Report anticipates the following by 2050:

a. Increasing temperatures in all seasons in all regions of British Columbia. The amount of warming will be greater than during the twentieth century.

b. Precipitation in winter, spring, and fall will likely increase in all of BC Hydro's watersheds under all emission scenarios.

c. BC Hydro will likely see a modest increase in annual water supply for hydroelectric generation.

d. Most Upper Columbia watersheds will see an increase in water supply. The snowmelt will start earlier, spring and early-summer flows will be substantially higher, and late-summer and early-fall flows will be substantially lower.

e. The Peace region will see an increased water supply. Inflows in late-fall and winter will increase; the snowmelt will begin earlier; and summer flows will be lower.

f. The Campbell River area and likely most Coastal watersheds will see negligible changes to annual water supply.

g. On the South Coast (Vancouver Island and Lower Mainland watersheds), more of the precipitation will fall as rain, while snow will become less important. Fall and winter flows will increase; and spring and summer flows will decrease.

18. The next step for BC Hydro is to feed operational and planning models with projected inflow scenarios to assess how sensitive hydroelectric power generation is to

climate change. It has not been determined how effectively reservoir storage will be able to buffer projected changes in seasonal runoff timing, such as lower summer inflows. There is thus uncertainty about the impact of climate change on this resource, uncertainty that BC Hydro is conducting research to resolve.

British Columbia's Carbon Tax

19. In 2008, British Columbia implemented the first comprehensive and substantial carbon tax in North America. By 2012, the tax had reached a level of C$30/t CO2, and covered approximately three-quarters of all greenhouse gas emissions in the province. In April 2018, it was again increased by $5/tCO2e, and is scheduled to increase to $50/tCO2e by 2021.

20. There have been a number of empirical studies of the consequences of British Columbia's carbon tax and other greenhouse gas policies, many of them canvassed in the affidavit of Nicholas Rivers, submitted by the Attorney General of Canada. The results of the studies conducted to date are summarized in Figure 7 at p. 25 of Exhibit B to Dr. Rivers' affidavit. As of 2015, the consensus view was that the carbon tax had reduced emissions from gasoline in British Columbia between 8% and 10%. A copy of a paper by Dr. Rivers and his co-author, Brian Murray, entitled "British Columbia's Revenue-Neutral Carbon Tax: A Review of the Latest 'Gran Experiment' in Environmental Policy is attached as **Exhibit I.**

21. The paper concluded, as of 2015, a total reduction between 5% and 15% compared with the counter-factual in which the tax had not been introduced.

Differential Greenhouse Gas Pricing and Competitiveness

22. As explored by the Ecofiscal Commission, the existence of different levels of carbon pricing in different provinces can create competitiveness pressures on industries that have a significant carbon footprint and are trade exposed when those industries are located in provinces with higher carbon prices. Carbon leakage occurs when firms that have significant carbon compliance liabilities under a carbon pricing framework compete with international firms that are not subject to the same constraints - as they are

typically unable to raise product prices or recoup compliance costs, they are forced to relocate outside of a carbon pricing jurisdiction to remain competitive (taking their emissions with them). These competitiveness concerns limit what a province like British Columbia can realistically do to take more aggressive action to reduce greenhouse gas emissions. A copy of the Ecofiscal Commission's 2015 report entitled "Provincial carbon pricing and competitiveness pressures" is attached as **Exhibit J** to this affidavit.

23. This report asserts based on expert research and analysis that carbon pricing in individual jurisdictions such as between provinces or countries—if not matched by equivalent carbon prices in other jurisdictions—can potentially create competitiveness pressures on individual sectors. The report defines a sector's "carbon costs," as a share of its GDP, and its "trade exposure."

24. A particular industry with high carbon use is the cement industry. A copy of an empirical study by Vincent Thivierge, examining impacts on B.C.'s cement industry from differential carbon pricing, is attached as **Exhibit K** to this affidavit. The analysis suggests that imports of cement increased as a result of the imbalance in carbon price between BC and other jurisdictions.

SWORN BEFORE ME at Victoria., British Columbia on December 18 2018.	)))	
______________________	))	______________________ Tim Lesiuk
A commissioner for taking affidavits for British Columbia J. Gareth Morley	))	

This is Exhibit A
referred to in the Affidavit
of Tim Lesiuk #2
sworn before me this 18th day
of December 2018

A Commissioner for taking Affidavits
within British Columbia

Timothy Lesiuk

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Experience

Executive Director, Clean Growth Strategy

Climate Action Secretariat, Province of British Columbia

- Coordinating development and engagement for a new climate change strategy for British Columbia that supports the province's economic, social and environmental goals.

Executive Director, Business Development and Chief Negotiator

Climate Action Secretariat, Province of British Columbia
2008 – Present

- Established systems and tools to ensure major capital and infrastructure decisions take into consideration future climate and carbon pricing scenarios.
- Supported development and engagement for the Climate Leadership Plan for British Columbia to advance actions to bring British Cloumbia closer to legislated climate change targets.
- Worked in collaboration with communities across the province to find innovative and cost-effective solutions to their highest cost and highest emitting energy and transportation problems through green community initiatives and greenhouse gas offset projects.
- Managed intergovernmental negotiations on climate and sustainability with western provinces and states, and the Canadian federal government, including regulatory harmonization and equivalency for greenhouse gas legislation.
- Developed an Innovation Exchange as the centre of the provincial Green Economy Strategy to facilitate collaboration across the complex array of stakeholders in the clean-tech, technology, energy and resource development fields to harness additional economic advantage for BC.

Executive Director, Climate Change Policy

Climate Action Secretariat, Province of British Columbia
2007 – 2008

- Accountable for negotiation of an international emissions trade agreement as Co-Chair of the Western Climate Initiative and established the largest emissions trading market in North America.
- Managed multiple cross-organizational teams and engagement with their respective industrial clients in a process designed to enhance collaboration and accelerate the regulatory process to reduce greenhouse gas emissions.

- Developed the concept and institutional infrastructure for the Pacific Carbon Trust, a new Crown Corporation created in legislation to build the greenhouse gas offset market in British Columbia.
- Accountable for strategic relations with each of British Columbia's most important industrial sectors in negotiating targets, identifying energy efficiency and performance improvements and securing financial incentives to enhance competitiveness.

Special Advisor, Environment and Climate Change

BC Hydro, Vancouver, British Columbia, Canada
2005 – 2007

- Strategic advisor for climate risk management in corporate planning, management of generating assets and energy purchase agreements.
- Built relationships with key stakeholders and led strategic engagement on environment and climate change issues regarding development of hydro and natural gas generation policy.
- Established the first corporate Long Term Environment goal of zero net environmental impact, and put in place internal environmental mitigation banking and auditing programs.
- Built executive and shareholder support to significantly expand investment in technology, innovation and Hydrogen programs.
- Led corporate climate team, established goals for corporate climate change risk management and implemented corporate greenhouse gas strategy with provincial and federal governments.

Senior Coordinator, Greenhouse Gas

BC Hydro, Vancouver, British Columbia, Canada
2003 – 2005

- Championed cross-corporation climate change risk management strategy and policy development.
- Led a strategic team to deliver custom needs assessments and innovative solutions to thermal business unit clients regarding asset investment, acquisitions and revenue opportunities.
- Established innovative standards for greenhouse gas quantification and reporting, risk assessment and integration in business cases.

Environmental Coordinator

BC Hydro, Vancouver, British Columbia, Canada
2000 – 2003

- Developed BC Hydro's greenhouse gas management strategy and international offset acquisition program.
- Negotiated contracts for Clean Development Mechanism, Joint Implementation, and Canadian domestic offset projects in excess of $300 million dollars in accordance with portfolio design criteria aligned to shareholder and corporate priorities.
- Expert participant in the negotiation of international greenhouse gas standards and protocols (World resources Institute GHG Protocol, World Business Council, Kyoto Protocol, ISO 14064).

Environmental Coordinator

Westcoast Energy/Centra Gas, Victoria, British Columbia, Canada
1997 – 2000

- Informed corporate strategy to take advantage of environmental and greenhouse gas emissions policy and participated in the first offset project for carbon capture and storage in Canada.
- Developed corporate standard for greenhouse gas inventories, piloted natural gas leak detection and measurement approaches for the natural gas system and represented the operating company in enterprise-wide policy development.
- Designed and implemented innovative community and stakeholder engagement programs for major project development.

Leadership and Advisory Roles

Western Climate Initiative Inc.
Board of Directors
2011 – 2017
A non-profit corporation established by California, British Columbia and Quebec to provide critical market infrastructure for California and provincial greenhouse gas emissions trading programs.

The Climate Registry
Executive Committee
2014 – 2017
A non-profit organization governed by U.S. states and Canadian provinces and territories that designs and operates voluntary and compliance GHG reporting programs globally, and assists organizations in measuring, verifying and reporting the carbon in their operations so they can manage and reduce it.

West Coast Infrastructure Exchange
Board of Directors
2013 – 2015
A non-profit corporation established by British Columbia, California, Oregon and Washington to create innovative new methods to finance and facilitate development of the infrastructure needed to improve the region's economic competitiveness, support jobs and families, and enhance our shared quality of life

Western Climate Initiative
Co-Chair and Offsets Committee Chair
2007 – 2012
A collaboration of eleven independent jurisdictions working to implement innovative emissions trading policies to tackle climate change at a regional level. Established the design and operation of the cap-and-trade program used by California and Quebec.

British Columbia Industrial Emitters Caucus, (Business Council of British Columbia)
Co-Chair

2005 –2007
Led committee of industrial members with operations in British Columbia concerned about the potential impacts of proposed climate and energy policy and provided a single voice for British Columbia industry on climate policy and competitiveness.

World Business Council for Sustainable Development (WBCSD)
Focus Area Leader
2005-2007
Established the WBCSD as the preferred business partner on ecosystem services while maintaining strong partnerships with key non-government organizations and engaging in global biodiversity and ecosystem policy development.

Canadian Electricity Association
Executive Representative
2002 - 2007
Defined preferred greenhouse gas policy for the electricity sector in Canada from this key industry perspective.

Education

- Bachelor of Science, Biology – University of Victoria (1993)
- Diploma of Technology, Environmental Science – Camosun College (1999)

This is Exhibit B
referred to in the Affidavit
of Tim Lesiuk #2
sworn before me this 18th day
of December 2016

A Commissioner for taking Affidavits
within British Columbia

Indicators of Climate Change for British Columbia

2016 Update

BRITISH COLUMBIA | Ministry of Environment

Revised
JUNE 2016

ABOUT THE COVER

Air temperature is an important property of climate and the most easily measured, directly observable, and geographically consistent indicator of climate change. Historical data show that the average annual temperature increased in most parts of British Columbia between 1900 and 2013. Temperatures increased by 0.8°C to 2.0°C throughout BC. Northern and interior regions of BC have warmed more rapidly than coastal regions. Atmospheric warming of this magnitude affects other parts of the climate system, including precipitation, air, wind and ocean currents, and the hydrological cycle. Climate change affects ecosystems and species, and has both positive and negative impacts on human communities.

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CONTENTS

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Indicators of Climate Change for British Columbia

Both the UN Intergovernmental Panel on Climate Change and the US National Academy of Science have concluded that the global atmosphere is warming. They agree, moreover, that most of the warming observed over the last 60 years can be attributed to human activities that release greenhouse gases into the atmosphere.

Atmospheric warming affects all parts of the climate system, including precipitation, air, wind and ocean currents, cloud cover, and the hydrological cycle. Climate change in turn affects other closely related physical systems, as well as biological systems, and the human communities that depend on these systems.

This report documents how the climate in British Columbia has changed during the 20th and early part of the 21st centuries and the rates at which these changes are occurring. It outlines some of the potential impacts of these changes on freshwater, marine, and terrestrial ecosystems and on human communities.

2015/2016 UPDATES

Portions of this report have been updated in 2015 and 2016 with new data and analysis. Each section is labelled to indicate whether the content is from the 2002 version or current.

CLIMATE CHANGE TRENDS

The trends described in this report are based on a set of environmental indicators that represent key properties of the climate system, or important ecological, social, or economic values that are considered sensitive to climate change. The report describes changes in these indicators over time. Past trends are based on analysis of historical data.

Details of these trends are presented in the body of this report, but some highlights are as follows:

Past trends

Analysis of historical data indicates that many properties of climate have changed during the 20th and early 21st centuries, affecting marine, freshwater, and terrestrial ecosystems in British Columbia.

- **Average annual temperature warmed by 1.4°C per century across the province.**
- **The northern regions of BC warmed more than the provincial average.**
- **Night-time temperatures increased across all of BC in all seasons.**
- **The night-time minimum average temperature in winter in BC increased by 3.1°C per century.**
- **Annual precipitation has been increasing across the province overall.**
- **Lakes and rivers become free of ice earlier in the spring.**
- **The bulk of river flow is occurring earlier in the year.**

- Average sea level has risen along most of the BC coast.
- Sea surface temperatures have increased along the BC coast.
- Water in the Fraser River is warmer in summer.
- More heat energy is available for plant and insect growth.

Projected impacts

Climate models and scenarios suggest that the climate in British Columbia will continue to change throughout and beyond the 21st century. This will have ongoing impacts on ecosystems and communities. Some of the impacts we may experience by the final decades of the 21st century are:

- Average annual temperature in BC may increase by 1.7°C to 4.5°C from 1961-1990 temperatures.
- Average annual precipitation may increase by 4 to 17 percent from 1961-1990 levels.
- Most small glaciers in southern BC will likely disappear.
- Some of the smaller rivers in southern BC may dry up during the summer and early fall.
- Salmon migration patterns and success in spawning are likely to change.

The indicators presented in this report document some of the changes that have occurred during the past century or more. Many more potential indicators remain to be explored. For example, climate change influences the frequency of extreme weather events, the extent of permafrost, ecosystem structures and processes, and species distribution and survival. It will continue to affect provincial infrastructure, forestry, energy and other industries, insurance and other financial services, and human settlements. In addition, the impacts may vary from one region, ecosystem, species, industry, or community to the next. Research into the regional impacts of climate change is ongoing, and this report is therefore designed to be updated and expanded as new information becomes available.

FOR MORE INFO

Information on historical trends is available on the Environmental Reporting BC website (gov.bc.ca/environmentalreportingbc). More information on projected impacts is available through the Plan2Adapt online tool (www.pacificclimate.org/analysis-tools/plan2adapt)

RESPONDING TO CLIMATE CHANGE

The impacts of climate change on British Columbians will depend on the time, the place, and the individual. For example, homeowners may see a warmer climate as a benefit if it means lower home heating bills. Resort operators may see it as a cost if it means a shorter ski season. Farmers may see it as a benefit if it allows them to introduce new crops, and as a cost if it increases the need for irrigation. Overall, however, the risk of negative impacts increases with the magnitude of climate change.

Much attention has been paid over the last decades to slowing down the rate of climate change by reducing greenhouse gas emissions. Success in this area has been mixed. Even if mitigation efforts are successful in reducing greenhouse gas emissions, they cannot prevent the impacts of climate change. The greenhouse gases humans have already added to the atmosphere will likely continue to drive sea level rise and other aspects of global climate change for centuries to come. British Columbia and other jurisdictions will therefore have to adapt.

In Canada, the federal, provincial, and territorial governments are developing adaptation frameworks and strategies. British Columbia's Adaptation Strategy was developed in 2010 and is available online. Many municipal governments are incorporating potential climate change impacts into long-term plans for drinking water supply, drainage, storm-water infrastructure and land-use.

A greater understanding of climate change trends and impacts is expected to help British Columbians prepare for and adapt to climate change at the same time as the province works to reduce the scale of future impacts through renewable energy, energy efficiency, sustainable transportation, new technology, water conservation, and other sustainable practices.

GLOBAL TRENDS

Where current global trends and future global projections are mentioned throughout the body of this report the information is from the Intergovernmental Panel on Climate Change (IPCC) AR5 report (available at www.ipcc.ch/). The key topics and trends that are referred to are easiest to find in the shorter report titled: *Climate Change 2014 Synthesis Report; Summary for Policymakers* (available at http://www.ipcc.ch/report/ar5/syr).

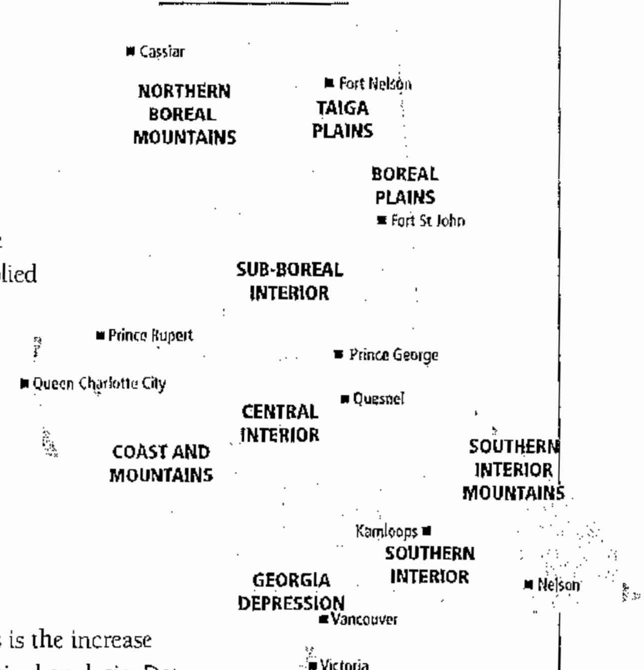
About the data and trends

This report was originally written in 2002 to document changes over the previous century in some of the key properties of the climate system and in some ecological, social or economic values that are considered sensitive to climate change. Sections of this report were brought up to date in 2015 and 2016, using new information about changes in temperature and precipitation from 1900 to 2013. These changes are referred to as trends.

Where possible, the report identifies trends for each region of the province. The geographical unit used is the ecoprovince – an area delineated by similar climate, topography, and geological history. Trends are identified when the changes are found to be statistically significant at the 95 percent confidence interval, which means that there is a less than 5 percent probability that the results ocurred by random chance.

For these updates the Pacific Climate Impacts Consortium (PCIC) assessed trends in annual and seasonal means of daily minimum, maximum, and mean temperature, precipitation, growing degree days, heating degree days, and cooling degree days. Trends were computed for the interval from 1900 through 2013 and for both BC as a whole and the nine terrestrial ecoprovinces of BC. PCIC also supplied assessments, based on remote sensing data, of glacier change from roughly the 1980s through the early 2000s through a collaboration with the University of Northern British Columbia (UNBC). PCIC also assessed trends in snow, river flow, sea level, and sea surface temperature.

Ecoprovinces of British Columbia



DATA

One reason to update BC's climate indicators is the increase in the amount of data available since the original analysis. Data quantities have increased both through the passage of time, but more importantly through the development of a comprehensive database of observations in BC. The Ministry of Environment's Climate Related Monitoring Program (CRMP) has negotiated an agreement to allow PCIC to assemble, store, and deliver data collected by BC Ministries, BC Hydro and RioTinto AlCan. The data set also includes de-activated historical networks. This assessment was conducted using the data from CRMP and Environment Canada. Altogether, the dataset comprises 6721 measurement locations and roughly 400 million observations, roughly double the data available in 2002. The data from Environment Canada, BC Hydro, the Ministry of Forests Lands and Natural Resource Operations Wildfire Management Branch, and Ministry of Transportation's observational network are incorporated in near real time for future analysis. For this analysis, only temperature and precipitation measurements were used from the station observational dataset.

This analysis requires stations with relatively long records. The early part of the analysis (early 1900's) are based on a sparse network of stations so any understanding of the detailed climate at that time is less certain than for more recent years when there are more stations distributed broadly across the province. This issue is most critical for precipitation. Precipitation distributions are hard to estimate across a larger area, and this is further complicated by British Columbia's complex topography. In this report we have chosen to report trends for the full period for precipitation, but acknowledge that the statistical uncertainty in the trends may not fully capture the uncertainty that arises from changes in the observational network over time. However, the trends reported here are broadly consistent with other analyses carried out at a coarser spatial resolution and at individual stations.

The changes to glaciers that have occurred in the past several decades and which are projected to occur with climate change were intensively studied through the Western Canadian Cryospheric Network which involved researchers from most universities in British Columbia. This report, relies on two separate studies; the first looked at the change in volume of the glaciers in British Columbia from roughly 1985 until winter 1999-2000. The second investigated the changes in glacier area from the period 1985 through 2005. Both resultant datasets cover all glaciers in British Columbia and thus provide an excellent snapshot of both the state of glaciers in the early 2000s as well as the changes those ice masses underwent during a very warm climatological period.

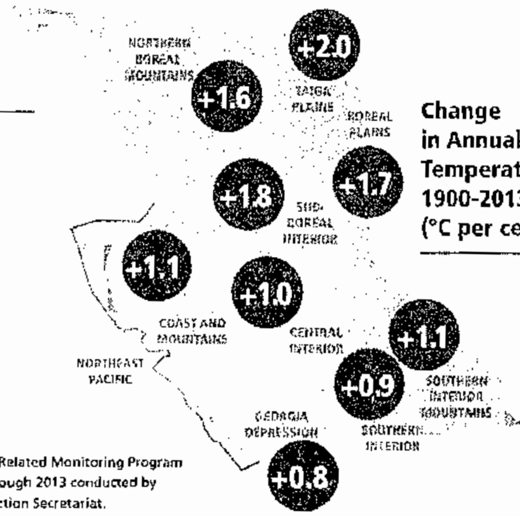
INTERPRETING THE TREND INFORMATION

- **This report presents only those results that were found to be significant at the 95 percent confidence interval. This means that there is a less than 5 percent probability that the results arose randomly.**
- **Where the data do not reveal a trend that is statistically significant at the 95 percent confidence interval, the report presents this as "NS" to indicate that the trend is not statistically significant.**
- **If there is insufficient data to calculate a trend the report presents no result.**

Revised 2015

Indicator: AVERAGE TEMPERATURE

Average temperature increased over all of BC from 1900 to 2013. Winter is warmer on average than it was 100 years ago. Higher temperatures drive other changes in climate systems and affect physical and biological systems in BC. They can have both positive and negative impacts on human activities.



Change in Annual Temperature, 1900-2013 (°C per century)

SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment Climate Action Secretariat.
NOTES: All statistically significant trends are positive and indicate warming.

ABOUT THE INDICATOR

This indicator measures changes in average annual temperature and average temperature in each of the four seasons. Trends are based on available data from 1900 to 2013 for each of the nine terrestrial ecoprovinces. Seasonal trends are based on averages for spring (March-May), summer (June-August), fall (September-November), and winter (December-February).

ANNUAL TEMPERATURE TRENDS

The province of BC has warmed an average of 1.4°C per century from 1900 to 2013, higher than the global average rate of 0.85°C per century. Southern coastal regions of BC have warmed 0.8°C per century, roughly equivalent to the global average rate. The Northern regions of BC have warmed 1.6°C to 2.0°C per century or twice the global average.

Average global temperatures increased by 0.85°C from 1880 to 2012 according to the Intergovernmental Panel on Climate Change (IPCC). The higher rate of warming in BC is consistent with findings in the IPCC reports that mid and higher latitudes in the Northern Hemisphere are warming faster than the global average and that land areas warm faster than the ocean. The IPCC 2014 *Climate Change Report Summary for Policy Makers* identifies the years from 1983 to 2012 as likely the warmest 30 year period in the last 1400 years in the Northern Hemisphere.

SEASONAL TEMPERATURE TRENDS

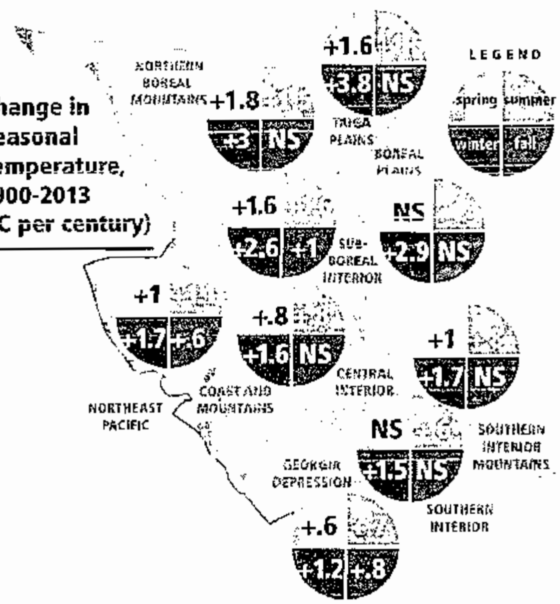
Most of the annual warming trend has occurred in the winter in BC. The average temperature increase in winter across the province is 2.2°C per century. Winter temperatures in the north of BC have increased by 3.0°C to 3.8°C per century. In the North-Central region, winters are 2.6°C to 2.9°C warmer than they were a century ago. In central, interior and southeastern BC, average winter temperatures have warmed 1.5°C to 1.7°C per century.

There is a province-wide warming trend in the spring and summer. The spring warming trend was 1.8°C per century in the Northern Boreal Mountains ecoprovince. The northeastern plains warmed 1.6°C per century in the spring. Spring has warmed by 1.0°C per century in both the coastal and southern interior mountains. Summer temperatures in most of northern BC have warmed 1.4°C to 1.6°C per century. In southern and central BC summer temperatures have warmed 0.6°C to 0.8°C per century.

There is no statistically significant province-wide warming trend in the fall. However, the coastal regions warmed by 0.6°C to 0.8°C per century in the fall and the sub-boreal interior warmed by 1.0°C per century. There was no significant trend for the rest of the province in the fall.

The date when each season arrives varies from one part of BC to the next, depending on climate, latitude, and elevation. Spring comes earlier to the coast, to southern BC, and to valley bottoms, for example, than it does to the north and alpine areas. The seasonal trends described in this document are based on calendar months, and as such may not reflect the way that disparate seasons are experienced in different parts of BC.

Change in Seasonal Temperature, 1900-2013 (°C per century)



SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment Climate Action Secretariat. NOTES: All statistically significant trends are positive and indicate warming. NS indicates that trend is not statistically significant.

WHY IS IT IMPORTANT?

Air temperature is one of the main properties of climate and the most easily measured, directly observable, and geographically consistent indicator of climate change. Atmospheric warming affects other parts of the climate system, and in BC is linked to sea surface warming and increased precipitation in some regions.

Changes in climate can affect other physical processes, including the duration of ice on rivers and lakes, the proportion of snow to total precipitation, and temperature in freshwater ecosystems. Such changes can in turn affect biological systems. Water temperature, for example, affects the date of emergence of the young of many aquatic species. Warming may drive broad-scale shifts in the distribution of ecosystems and species. Trees may be able to grow in areas once too cold for them. Some alpine meadows may disappear as high-elevation areas become warmer. Beneficial and pest species may appear further north, or higher in elevation, than their historic range.

The impacts of warmer temperatures will vary from one part of BC to another and from one season to another. They will have both positive and negative impacts on human activities.

Warmer springs may promote earlier break up of lake and river ice, and resulting changes in river hydrology including possible flooding. They may mean a longer season for warm-weather outdoor recreation activities and a longer growing season for crops.

Warmer summers may increase rates of evaporation and plant transpiration. Reduced moisture may contribute to dust storms and soil erosion, increased demand for irrigation, loss of wetlands, slower vegetation growth, forest fires, and the conversion of forest to grasslands. It may contribute to declines in ground-water supplies and in water quality in some areas. Higher temperatures may increase temperatures in freshwater ecosystems, creating stressful conditions for some fish species.

Warmer winters may mean that less energy is required to heat buildings. They may mean a shorter season for skiing and other winter sports and losses in the winter recreation sector.

WHY IS TEMPERATURE INCREASING?

Air temperature in BC is strongly affected by El Niño and other natural changes in air and ocean currents (see Appendix), which cause year-to-year and decade-to-decade variability in weather and climate across the province. The warming trends observed during the 20th and 21st century are above and beyond trends that could have been produced by such natural variability, and almost certainly reflect long-term climate change. The rate of warming is greater in more northerly regions. As air temperature increases, snow and ice melt, exposing more of the ground and sea surface. While snow and ice tend to reflect solar energy back into space, newly exposed rocks, soil, and water tend to absorb and retain it as heat.

The IPCC has concluded that most of the observed global atmospheric warming of the last 50 years is due to increases in atmospheric greenhouse gas concentrations. Greenhouse gas emissions resulting from a variety of human activities, including the burning of fossil fuels and the clearing of land for agriculture and urban development, are responsible for this increase.

WHAT CAN WE EXPECT IN FUTURE?

Average annual temperature across BC will continue to vary from year to year in response to natural cycles in air and ocean currents. However, what are now considered to be relatively warm years will almost certainly increase in frequency.

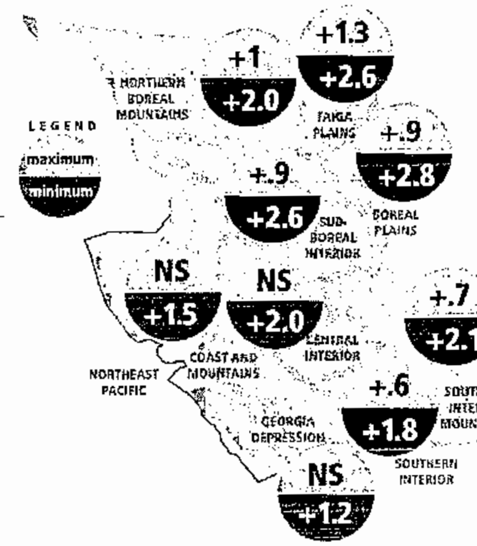
Plan2Adapt projects further warming in BC of 1.7°C to 4.5°C by the 2080s compared to the 1961-1990 historical average. The interior of the province will warm faster than other areas and will experience higher rates of warming than in the past. The north will continue to warm at rates considerably greater than the global average. Ocean temperatures have a moderating effect on the climate of the coast, which will warm more slowly than the rest of BC. More information about expected future climate indicators in BC is available at Plan2Adapt (www.pacificclimate.org/analysis-tools/plan2adapt).

Although temperature increases of a few degrees may seem small, they are associated with important physical and biological changes. A rise in average temperature of 5°C about 10,000 years ago was enough to melt the vast ice sheets that once covered much of North America.

Revised 2015

Indicators: MAXIMUM AND MINIMUM TEMPERATURE

Night-time minimum temperatures in BC are warmer on average than they were a century ago. The increase in minimum temperature is particularly noticeable in the winter season and the northern regions of BC. In winter and spring, higher minimum temperatures may reduce heating costs and in some parts of BC may also increase the frequency of freeze-thaw cycles. In the summer they may prevent buildings from cooling down during the night.



Change in Annual Maximum and Minimum Temperature, 1900-2013 (°C per century)

SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment Climate Action Secretariat. NOTES: All trends are positive and indicate warming. NS indicates that trend is not statistically significant.

ABOUT THE INDICATORS

The indicators measure change in the annual average daily (day-time) maximum temperature and the annual average daily (night-time) minimum temperature. They also measure changes in maximum and minimum temperature in each of the four seasons. Trends are based on available data from 1900 to 2013. Seasonal trends are based on averages for spring (March-May), summer (June-August), fall (September-November), and winter (December-February).

TRENDS IN MAXIMUM TEMPERATURE

From 1900 to 2013, annual day-time maximum temperatures increased in BC by an average of 0.7°C per century. Annual day-time maximum temperatures increased by 1.0°C to 1.3°C per century in the Taiga plains and Northern Boreal Mountains ecoprovinces. In the Sub-Boreal and Boreal Plains ecoprovinces the annual day-time maximum temperatures increased by 0.9°C per century. In three other ecoprovinces (Georgia Depression, Coast and Mountains, Central Interior) the data do not reveal statistically significant trends in annual maximum temperature.

Seasonal data indicate that day-time maximum winter temperatures increased across most of BC. The average winter day-time maximum temperature increased by 1.9°C per century. Maximum day-time spring temperatures are increasing in the north of BC, but data do not reveal a statistically significant trend in the southern half of the province. For all of BC, data do not reveal a trend in day-time maximum temperature in the summer and fall.

The greatest increases in maximum day-time temperatures are found in the north. Winter day-time maximum temperatures increased by 3.0°C to 3.3°C per century in the Boreal Plains and Taiga Plains ecoprovinces. In the Sub-Boreal Interior and the Northern Boreal Mountains ecoprovinces the winter day-time maximum temperatures increased by 2.3°C to 2.6°C per century. In the three interior ecoprovinces the winter day-time maximum temperature increased by 1.2°C to 1.6°C per century.

In the spring the northern ecoprovinces (Sub-boreal Interior, Boreal Plains, Taiga Plains, Northern Boreal Mountains) warmed by 1.1°C to 1.5°C per century. The southern half of BC showed no trend in the spring for changes in day-time maximum temperature.

In the Georgia Depression ecoprovince there was no trend in the data for day-time maximum temperature for any season.

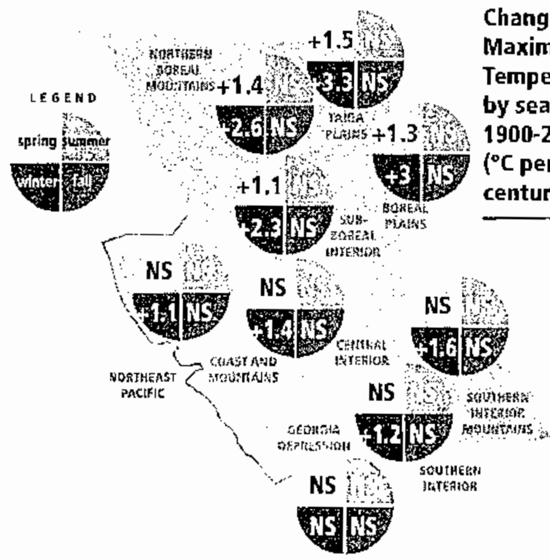
TRENDS IN MINIMUM TEMPERATURE

Annual night-time minimum temperatures increased across BC an average of 2.0°C per century from 1900 to 2013. The greatest increase in minimum temperature has been recorded in the Boreal Plains ecoprovince, where daily minimum temperature increased at a rate equivalent to 2.8°C per century. In the Taiga Plains and Sub-Boreal Interior ecoprovinces the annual daily minimum temperature increased 2.6°C per century. On the coast (Georgia Depression and Coast and Mountains) the annual night-time minimum temperatures increased 1.2°C to 1.5°C per century.

Seasonal data indicate that night-time minimum temperatures increased across all of BC for all seasons. The average night-time minimum temperature increased in winter for the province at 3.1°C per century.

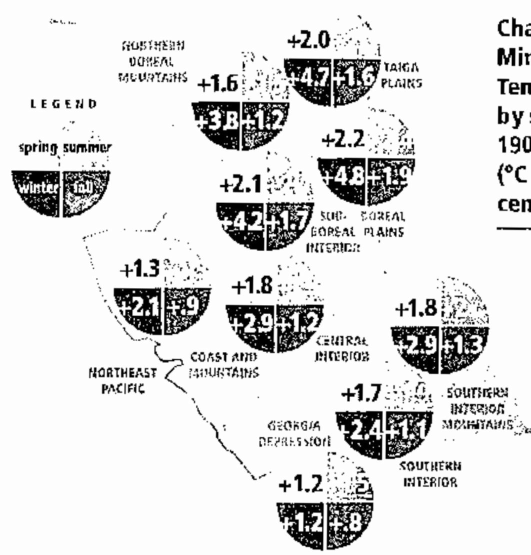
In the Boreal Plains the night-time minimum temperature increased at the greatest rate for all ecoprovinces, in all seasons. In the winter, in the Boreal Plains ecoprovince, the night-time minimum temperature increased by 4.8°C per century, in spring it increased by 2.2°C per century, in summer by 2.4°C per century and in fall by 1.9°C per century. In contrast, in the Georgia Depression ecoprovince, the night-time minimum temperature increased at a rate equivalent to 1.2°C in the winter, 1.2°C in the spring, 1.5°C in the summer and 0.8°C in the fall. In the interior (Central Interior, Southern Interior and Southern Interior Mountains) the night-time minimum temperature increased by 2.4°C to 2.9°C per century in the winter, in the spring it increased by 1.7°C to 1.8°C per century, in the summer by 1.9°C to 2.0°C per century and in the fall by 1.1°C to 1.3°C per century.

The night-time minimum temperature increased in the winter in the Taiga Plains ecoprovince by 4.7°C per century, and in the Sub-Boreal Interior ecoprovince by 4.2°C per



Change in Maximum Temperature, by season, 1900-2013 (°C per century)

SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment Climate Action Secretariat. NOTES: All statistically significant trends are positive and indicate warming. NS indicates that trend is not statistically significant.



Change in Minimum Temperature by season, 1900-2013 (°C per century)

SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment Climate Action Secretariat. NOTES: All statistically significant trends are positive and indicate warming.

century. In both ecoprovinces the summer night-time minimum temperature increased by 2.1°C per century.

WHY IS IT IMPORTANT?

The strong, increasing trends in minimum temperature, especially during the winter, have likely made the greatest contribution to the general warming trends across the province. In regions and in seasons where trends in both minimum and maximum temperatures were observed, minimum temperatures increased faster than maximum temperatures over the record period. As a result, the temperature range during the average day has decreased.

The Intergovernmental Panel on Climate Change (IPCC) has concluded that the increase in minimum temperatures has lengthened the freeze-free season in many mid-and high-latitude regions. Higher night-time minimum temperatures in fall, winter, and spring may enhance the growing conditions for both valuable and pest plant and insect species and decrease heating costs. In summer, they may increase heat-related stress in humans and other species because buildings and habitats may not be able to cool down adequately at night. In some parts of BC, freeze-thaw cycles may increase in frequency.

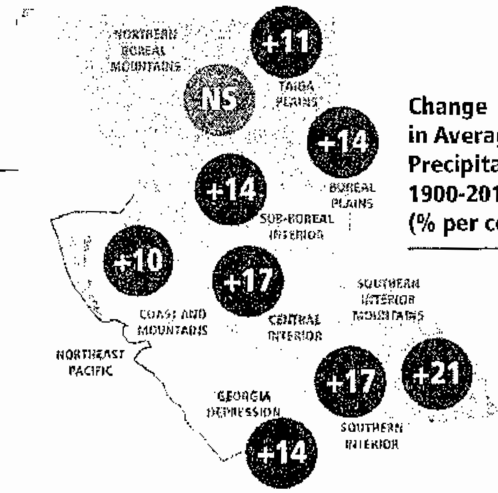
WHAT CAN WE EXPECT IN FUTURE?

Climate models project that in the 21st century, night-time lows in many areas will continue to increase more than day-time highs. A number of models suggest that in the Northern Hemisphere the gap between the daily maximum and the daily minimum will decrease in winter and increase in summer.

Revised 2015

Indicator: PRECIPITATION

Average precipitation increased over most of southern BC from 1900 to 2013. More water may be available to recharge groundwater aquifers, maintain river flows, and replenish soil moisture. Hydroelectric power generation, irrigation, and domestic water use may benefit. In some seasons, increased runoff may increase the chance of landslides and debris torrents, or exceed the capacity of municipal drainage and sewage systems.



Change in Average Precipitation, 1900-2013 (% per century)

SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment.
NOTES: All statistically significant trends are positive and indicate increasing precipitation. NS indicates that trend is not statistically significant.

ABOUT THE INDICATOR

The indicator measures changes in annual average daily precipitation at weather stations across BC. It also measures changes in average daily precipitation in each of the four seasons. Trends are based on data from 1900 to 2013. While these trends are reported for the whole period from 1900 to 2013, at the beginning of that time period the network of weather stations was relatively sparse through BC. The statistical uncertainty in the trends may not fully capture the uncertainty that arises from changes in the observational network over time. However, the precipitation trends reported here are broadly consistent with other analyses carried out at a coarser spatial resolution and at individual stations.

Seasonal trends are based on averages for spring (March-May), summer (June-August), fall (September-November), and winter (December-February).

ANNUAL PRECIPITATION TRENDS

Province-wide average annual precipitation has increased by 12 percent per century. Average annual precipitation increased by 17 percent per century in the Southern Interior and by 21 percent per century in the Southern Interior Mountains ecoprovinces.

Precipitation in the Central Interior increased by 17 percent per century. Precipitation increased in the Coast and Mountains ecoprovince by 10 percent per century. In the Georgia Depression ecoprovince, precipitation increased by 14 percent per century.

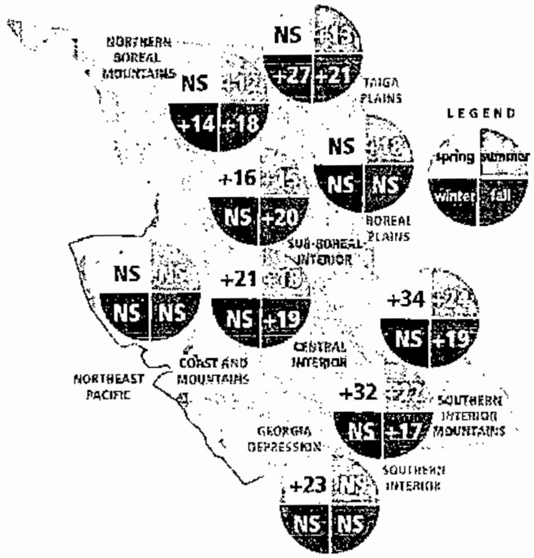
In the Sub-Boreal Interior and the Boreal Plains ecoprovinces average annual precipitation has increased by 14 percent per century. The data do not indicate a statistically significant trend for the Northern Boreal Mountains.

SEASONAL PRECIPITATION TRENDS

Trends in seasonal precipitation are varied through BC. Through most of the province, the data do not indicate statistically significant trends in winter precipitation. And, the data do not indicate seasonal trends in the Coast and Mountains ecoprovince.

In the Georgia Depression ecoprovince, precipitation has increased by 23 percent per century in the spring, and the data do not indicate

Change in Seasonal Precipitation, 1900-2013 (% per century)



SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment.
NOTES: All statistically significant trends are positive and indicate increasing precipitation. NS indicates that trend is not statistically significant.

any seasonal precipitation trends in other seasons. In the Boreal Plains ecoprovince, precipitation has increased by 18 percent per century in the summer and the data do not indicate any seasonal trends for any other seasons.

In the interior and southern coast of BC, precipitation is increasing in the spring months. In the Taiga plains and the Northern Boreal Mountains ecoprovinces, the precipitation trends indicate an increase in precipitation in the winter, summer and fall, but not in the spring. In the four interior ecoprovinces in BC there is a trend towards increasing precipitation in the spring, summer and fall, but not in the winter.

The date that each season arrives varies from one part of BC to the next, depending on climate, latitude, and elevation. The seasonal trends described here are based on calendar dates, and may therefore fail to reflect the seasons well for some parts of BC.

WHY IS IT IMPORTANT?

Precipitation is a fundamental aspect of climate and a key indicator of climate change. It is highly variable across BC as a consequence of topography and natural climate variability. Mountain slopes that face the prevailing westerly winds receive considerably more rain than leeward slopes or adjacent valleys.

Natural and human systems are adapted to such variability. Climate change, however, may mean a shift to warmer, wetter years, more frequent wet years, greater year-to-year variability, and more extreme precipitation events. Long-term changes in the amount, form, and timing of precipitation have significant impacts on freshwater and terrestrial ecosystems as well as on human activities. The impacts will vary depending on season, and some impacts may carry over from one season to the next.

In general, an increase in precipitation suggests that more water is available for natural systems, to recharge groundwater aquifers, maintain river flows, replenish soil moisture, maintain wetlands and marshes, and support plant growth. Human activities that depend on water supply – including hydroelectric power generation, irrigation, domestic water use, and some industrial processes – may benefit. Increased precipitation may also be responsible in some areas and in some seasons for increased flooding and damage to ecosystems and infrastructure. Increased year-to-year variability in precipitation may have adverse impacts on wetlands and other ecosystems and make water planning more complex.

- Where winter precipitation falls as snow – in the interior and north of BC, for example – an increase in precipitation may help local economies based on skiing and other winter recreation activities, but increase the cost of road maintenance and accidents. Snow build-up during the winter may increase the amount of water released into streams and rivers in spring and summer when the snow melts.
- Where winter precipitation falls as rain – on the coast, for example – an increase in precipitation may increase winter runoff, exceeding the capacity

of municipal drainage and sewage systems and reducing water quality.

WHY IS PRECIPITATION INCREASING?

Atmospheric warming is a component of climate change. Warmer air can hold more water vapour, pick up water faster from the earth, lakes, and oceans, and carry more moisture to the land, where it falls as rain or snow. Thus atmospheric warming is associated with a global increase in precipitation over land.

In BC, prevailing winds carry moisture inland from the Pacific Ocean. As the air rises over coastal mountains, it cools, releasing moisture. Average surface temperatures of the ocean and the land increased during the 20th century. As a result, winds carry more moisture from the ocean to the coast and the interior of the province.

WHAT CAN WE EXPECT IN FUTURE?

Average annual precipitation across BC will continue to vary from year to year in response to natural cycles in air and ocean currents. Relatively wet years, however, will almost certainly increase in frequency through the end of the century.

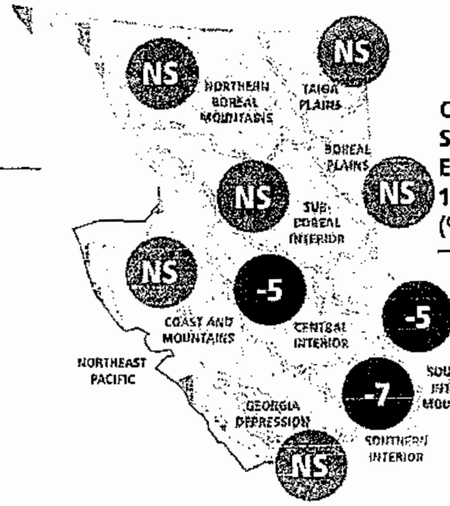
Climate models project that average annual precipitation in the mid-latitudes of the Northern Hemisphere will continue to increase. Precipitation is projected to increase by 4 to 17 percent by the 2080s compared to the 1961-1990 historical average, according to PCIC's Plan2Adapt tool. Winter precipitation is projected to increase from 5 to 23 percent in the province as a whole by the 2080s. As temperatures increase, more winter precipitation will fall as rain rather than snow. More information about future climate in BC can be found online at Plan2Adapt (http://www.pacificclimate.org/analysis-tools/plan2adapt).

Annual averages for precipitation do not tell us a lot about how and when that precipitation occurs. According to the IPCC, frequency and intensity of heavy precipitation events has likely increased in North America since 1950 due to climate change. The frequency and intensity of heavy precipitation events is likely to increase in BC through the 21st century. This could result in an increase in extreme precipitation events (heavy rain and snow) and the possibility of increased localized flooding.

Revised 2016

Indicators: SNOW

The water content and the depth of snow is decreasing, resulting in higher snow density in some parts of BC. Changes in snowpack affect the amount of water that is stored over the winter and released to groundwater aquifers, streams, and rivers in the spring and summer. These changes may affect the timing of snowmelt and local heat exchange processes.



Change in Snow Water Equivalent, 1950-2014 (% per decade)

SOURCE: Data provided by the River Forecast Centre, Ministry of Forests, Lands and Natural Resource Operations, and Ministry of Environment. Analysis by PCIC 2016, for Ministry of Environment. Notes: All statistically significant trends are negative and indicate decreasing SWE. NS indicates that trend is not statistically significant.

ABOUT THE INDICATOR

The indicators measure changes in snow depth and snow water equivalent (SWE), the amount of water that is contained in the snow pack. Together, the measures provide information about snow density. Trends are based on data collected at provincial snow survey stations in spring (April 1) between 1950 and 2014. Most stations are located between 1,000 and 2,000 metres above sea level.

SNOW TRENDS IN BRITISH COLUMBIA

Trends in SWE and snow depth in BC are not uniform across the regions studied.

In the Southern Interior Mountains, SWE decreased at a rate of 5 percent per decade. Snow depth decreased at a rate of 7 percent per decade.

In the Central Interior, SWE decreased at a rate of 5 percent per decade. Snow depth decreased at a rate of 10 percent per decade.

In the Southern Interior SWE decreased at a rate of 7 percent per decade. Snow depth decreased at a rate of 11 percent per decade.

In the Boreal Plains, Georgia Depression, the Northern Boreal Mountains, and Taiga Plains ecoprovinces, there have not been significant SWE trends. Snow depth in the Georgia Depression decreased by 6 percent per decade.

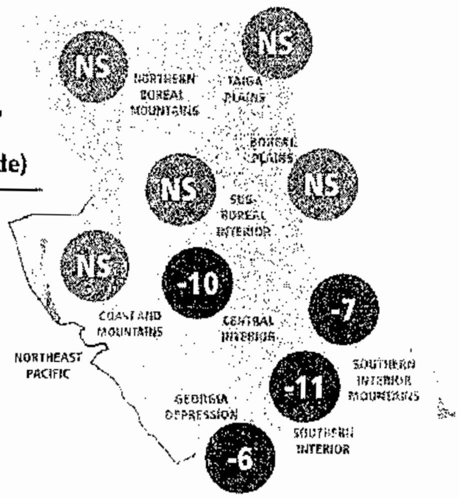
Together, SWE and snow depth provide information about snow density. In general, as SWE increases for the same volume of snow, or as depth decreases while SWE remains constant, density increases. Snow density has increased in four ecoprovinces; the three where snow depth decreased at a faster rate than SWE, and the one where SWE showed no significant trend but depth decreased.

WHY IS IT IMPORTANT?

Snow acts as a temporary storage system for winter precipitation, and SWE is a measure of how much water is stored as snow. When snow melts in spring and early summer, this water becomes available to recharge groundwater aquifers, fill reservoirs, and replenish soil moisture.

Many rivers in BC are snowmelt-fed, meaning they are characterized by a surge of water when snow melts in the spring and early summer. This influx of meltwater helps keep temperatures at a comfortable level for fish and other aquatic organisms. In many parts of BC, it also ensures that enough water is available in summer for irrigation,

Change in Snow Depth, 1950-2014 (% per decade)



SOURCE: Data provided by the River Forecast Centre, Ministry of Forests, Lands and Natural Resource Operations. Analysis by PCIC, 2016, for Ministry of Environment. Notes: All statistically significant trends are negative and indicate decreasing snow depth. NS indicates that trend is not statistically significant.

hydro-electric power generation, industry, fisheries, and domestic water use.

Snow depth affects the capacity of snow to act as an insulator. In general, the deeper the snow, the greater its insulating value. Changes in snow depth may therefore affect the local rate of heat exchange between the land and water and the atmosphere, and the rate and time at which ice melts.

Snow density can affect the timing and rate of melting. Denser snow is closer to its melting point. Increasing density may signal earlier or more rapid spring melting. Heavy rainfall on top of dense, wet snow can trigger rapid melting and flooding and damage to ecosystems and infrastructure.

The geographical extent of snow cover is as important as its physical characteristics. Satellite data show that in the Northern Hemisphere, the extent of early spring snow cover has decreased by about 10 percent from pre-1970 values. This has adverse implications for recreational winter sport activities and related economies. It may also contribute to local warming as exposed ground absorbs and retains heat.

WHY IS THE SNOWPACK CHANGING?

Snow accumulation and its characteristics are the result of air temperature, precipitation, storm frequency, wind, and the amount of moisture in the atmosphere. Changes in these and other climate properties can therefore affect snowpack.

Winter warming is the most likely cause of increasing snow density. As winter temperatures warm, more winter precipitation is likely to fall as heavy "wet" snow. Rain or sleet may compact snow already on the ground. Warmer air temperatures can cause snow already on the ground to melt onto itself.

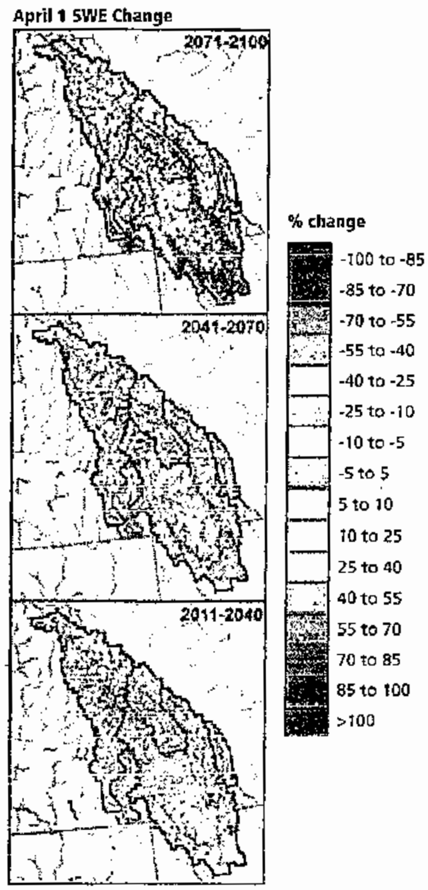
Temperature also affects the altitude of the snowline in mountainous areas and hence the total size of the area above the snowline. As temperature increases, the area above the snowline shrinks. This in turn affects the proportion of total precipitation that falls and is stored as snow and the amount of runoff in spring and summer.

The Intergovernmental Panel on Climate Change (IPCC) has concluded that there is a highly significant correlation between increases in surface temperatures and decreases in the extent of snow and ice in the Northern Hemisphere.

WHAT CAN WE EXPECT IN FUTURE?

The amount of precipitation that falls as snow will continue to vary from year to year in response to natural climate cycles. Climate models project, however, that as the Earth continues to warm, the extent of snow cover in the Northern Hemisphere will continue to decrease during the 21st century. The IPCC has concluded that in mountainous regions of North America, particularly at mid-elevations, higher temperatures could lead to a long-term reduction in peak snow-water equivalent, with the snowpack building later in the year and melting sooner.

Projected Change in Snow-Water-Equivalent in the Canadian Portion of the Columbia River Basin, 2011-2100

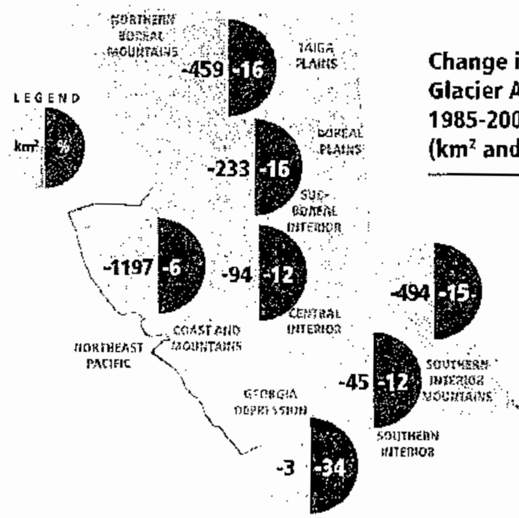


Projections of April 1 snowpack for three future periods show reductions at lower elevations and increases at higher elevations as the 21st century progresses. The snowpack retreats to higher elevations, reducing its area progressively through the century. The lowest elevations are projected to lose the majority of their snowpack by volume by the end of the century while higher elevations will see modest gains in snow. Overall, less water will be stored as snow in the future and this storage will occur at higher elevations than historically. SOURCE: Adapted from Werner, et al. (2013).

Revised 2015

Indicator: GLACIERS

All glaciers in BC retreated from 1985 to 2005. In the short term, retreating glaciers add water to glacier-fed streams and rivers. In the long term, this retreat will decrease late summer to early autumn runoff for these rivers.



Change in Glacier Area 1985-2005 (km^2 and %)

SOURCE: Bolch et al. (2010) NOTES: All changes are negative and indicate decreasing area.

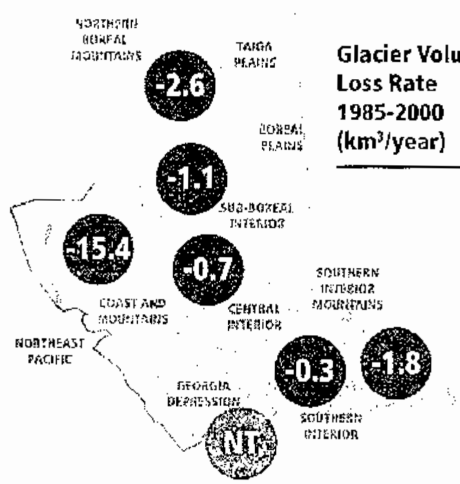
ABOUT THIS INDICATOR

Glaciers advance and retreat in response to changes in climate over time scales from decades to centuries. Glaciers thus respond to long-term changes in climate. This report includes two indicators of change in glacier coverage in BC. The first indicator is a measure of the change in area covered by glaciers in BC. Glacier area change was assessed by comparing the mapped extents of glaciers from the BC Terrain Resource Information Management (TRIM) program in 1985 with Landsat satellite imagery from 2005. The second indicator is the rate of change in the volume of glacier ice. Glacier volume change was assessed by differencing the topography measured during the TRIM campaign from the topography measured during the shuttle radar tomography mission (SRTM) in 2000.

Note that there are no glaciers in the Taiga Plains or Boreal Plains ecoprovinces of BC, so no results are reported for those regions.

GLACIER AREA CHANGES

From 1985 to 2005 the glacier coverage in the province as a whole decreased by 2525 km^2. Most of the glaciers in BC are in the Coast and Mountains ecoprovince, so while there was a large area of ice coverage lost, it corresponded with a smaller percentage area loss than southern and central regions of BC. The glaciers in the Georgia Depression ecoprovince are primarily on Vancouver Island, and those had the greatest percent area loss in the province. The area of glaciers in this region is small, however, so this represents a small change in the overall glacier ice cover of BC. The Central Interior ecoprovince lost 12 percent of the area of glacier ice coverage from 1985 to 2005. The Northern Boreal Mountains, Sub-Boreal Interior and Southern Interior Mountains lost 15 to 16 percent of the area of glacier ice coverage.



Glacier Volume Loss Rate 1985-2000 (km^3/year)

SOURCE: Data from Schiefer et al. (2007) NOTES: All changes are negative and indicate loss of volume. NT indicates that there was no trend.

TRENDS IN GLACIER VOLUME LOSS RATE

From 1985 to 2000 the province of BC lost 21.9 km^3 per year of ice from glaciers. As the Coast and Mountains ecoprovince has the most ice by volume, it also experienced the greatest volume loss rate. The Northern Boreal Mountains have the second largest area of ice in the province and are currently experiencing the second largest volume loss. We see from the temperature indicators that this is also where the most dramatic warming is occurring and this is likely driving the volume loss. The volume loss rate in the Sub-Boreal Interior and Southern Interior Mountains ecoprovinces equaled 1.1 and 1.8 km^3 per year, respectively.

Although the glaciers on Vancouver Island (Georgia Depression ecoprovince) had the greatest percentage area change, they are small glaciers so estimates of the volume loss rate are uncertain. The estimated volume change is near zero for the period, but confidence in this number is low.

WHY IS IT IMPORTANT?

Glacial meltwater feeds many mountain streams and rivers in BC, including the Cheakamus River, Pemberton Creek, Slesse Creek, Homathko River, Lillooet River, and Squamish River. In glacier-fed rivers, the highest flows tend to occur in early or mid-summer, depending on latitude, and glacier runoff can account for a significant portion of the available water supply.

Glacier retreat is therefore likely to cause changes in the flow timing and temperature of some streams and rivers. These changes – along with other climate-driven changes to hydrological systems (see "Freezing and Thawing") – will likely have significant impacts on freshwater and estuarine ecosystems and on aquatic species. They will affect other biological systems and human activities that depend on water.

In the short term, melting glaciers will likely discharge more water into some BC streams and rivers. This may provide short-term benefits to hydroelectric power generation, water-based recreation, irrigation, fisheries, and other water users. Higher flows may also, however, increase stream turbidity and damage fish habitat and riparian areas.

In the longer term, glacier retreat will likely mean reduced water volume in glacier-fed streams and rivers, especially during the summer months. In water-short regions, this could generate increased competition between various water users.

WHY ARE GLACIERS MELTING?

The advance or retreat of a glacier represents the integration of many climate-related events that may occur over a period as short as one year or as long as centuries.

Climate models suggest that for most glaciers, changes in temperature, rather than changes in precipitation, control the evolution of glacier ice volume. Although winter precipitation fuels the growth of a glacier, a warm summer can melt large gains from more than one previous year. The IPCC assesses that warmer temperatures associated with climate change are the cause of world-wide glacial melting.

WHAT CAN WE EXPECT IN FUTURE?

Glaciers and ice caps are projected to continue their widespread retreat through the 21st century. Globally, the actual rate of retreat will depend on the rate at which the temperature increases. The retreat of most glaciers will accelerate, and many small glaciers may disappear. Areas that are currently marginally glaciated are likely to become ice-free in future.

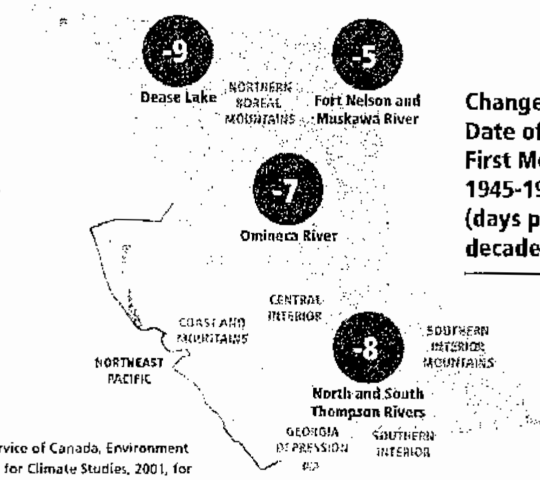
In BC, glaciers will continue to retreat throughout the province. The smaller glaciers in the southern ecoprovinces are likely to disappear by the end of the 21st century. Even glaciers with a high proportion of their surface at high elevations will continue to retreat.

2002 edition

Indicators: FREEZING AND THAWING

Ice on lakes and rivers in BC melts earlier now than it did several decades ago. When ice melts earlier in the spring, it can affect lake productivity, aquatic ecosystems, and winter activities.

Change in Date of First Melt, 1945-1993 (days per decade)



SOURCE: Data from Meteorological Service of Canada, Environment Canada. Analysis by Canadian Institute for Climate Studies, 2001, for Ministry of Water, Land and Air Protection. NOTES: A negative trend means that water bodies start to melt earlier in the year.

ABOUT THE INDICATORS

The indicators measure changes in the dates on which key freezing and thawing events occur on lakes and rivers in British Columbia. They are:

- date of first melt
- ice-free date (when rivers and lakes are completely free of ice)
- first date of permanent ice
- date of complete freezing

Trends are based on data from six (and for one indicator, seven) stations. The records span 27 to 51 years, and most cover approximately three decades.

MELTING AND FREEZING TRENDS

Lakes and rivers now start to melt earlier in spring, on average, than they did several decades ago. First melt has become earlier by 9 days per decade in Dease Lake, 5 days per decade in Fort Nelson, 7 days per decade in Omineca River, and 8 days per decade in the Thompson River region.

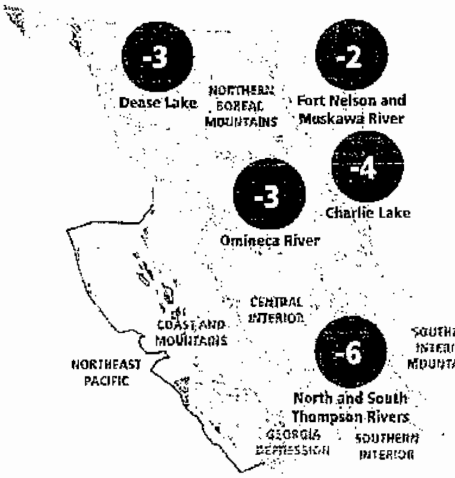
Lakes and rivers also become free of ice earlier, on average, than they did several decades ago. The ice free date has become earlier by 6 days per decade in the Thompson River region, 3 days per decade in Omineca River, 4 days per decade at Charlie Lake, north of Fort St. John, 3 days per decade at Dease Lake, and 2 days per decade at Fort Nelson.

Lakes and rivers in northern BC may freeze later in the fall, on average, than they did several decades ago. At Charlie Lake, the first permanent ice appears 5 days per decade later. At Fort Nelson, lakes freeze over completely 4 days per decade later. These trends are not replicated in adjacent stations and are considered weak.

The Intergovernmental Panel on Climate Change (IPCC) has concluded that the annual duration of lake and river ice in the mid-latitudes of the Northern Hemisphere probably decreased by about two weeks during the 20th century, or at a rate of 1 to 2 days per decade. It is difficult to compare the BC trends with this global average because the BC trends are based on data collected during a shorter, relatively warm period. The BC trends likely reflect climate variability rather than climate change.

WHY IS IT IMPORTANT?

The duration of ice on lakes and rivers is important for transportation. Vehicles involved in winter logging and oil and gas exploration can move about more easily when water bodies are frozen. Skiers and snowmobilers can use frozen lakes and rivers as backcountry roads.



Change in Ice Free Date, 1945-1993 (days per decade)

SOURCE: Data from Meteorological Service of Canada, Environment Canada. Analysis by Canadian Institute for Climate Studies, 2001, for Ministry of Water, Land and Air Protection.
NOTES: A negative trend means that water bodies are ice-free earlier in the year.

The duration of ice can also affect the productivity of freshwater ecosystems. The temperature of most lakes varies depending on depth. When lakes are cold – at high latitudes, at high elevations, or in winter – water at the bottom of the lake is warmer than water at the top. When lakes are warm – in low- to mid-elevations and latitudes, and in summer – water at the bottom of the lake is colder than water at the top. In spring and fall, many lakes go through a period in which temperature differences and thermal stratification disappear. This allows the water, and the nutrients, oxygen, and micro-organisms it contains, to mix throughout the lake, increasing productivity.

In lakes that currently undergo thermal stratification in summer, a longer ice-free period means that stratification develops earlier in the year and lasts longer. Periods of mixing during spring and fall may be reduced in length. Increasing temperatures mean that some lakes that currently freeze over in winter may no longer do so. They may move from a regime that includes winter stratification to one that includes winter mixing.

The IPCC has concluded that changes in thermal regimes and lake-mixing properties may have a significant effect on the concentration of dissolved oxygen in the deeper layers of many lakes, and consequently on available fish habitat. They may also affect primary productivity – the growth of phytoplankton – in the upper layers of these lakes, with impacts on fish production. The direction and magnitude of these effects will vary depending on the unique characteristics of the lake.

Many aquatic systems are sensitive to temperature, and thawing and freezing events may mark milestones in their life cycles. A longer ice-free season may mean a longer growing season for these organisms. It may allow some species to move into new areas that were previously not habitable to them.

WHY IS THE ICE MELTING EARLIER?

Climate affects the formation, thickening, and melting of ice – processes that reflect the beginning and end of the cold season and its severity. Air temperature is the main influence on the rate of heat loss and gain from water bodies and the timing of freeze-up and melt. Other contributing factors include cloudiness, solar radiation, wind speed, humidity, precipitation, the depth and composition of snow on top of the ice, and water temperature. All of these factors reflect local climate conditions.

During the past century, almost all regions of BC have experienced warmer spring temperatures (see "Average Temperature"). Earlier dates of first melt and ice breakup are consistent with these trends.

The IPCC attributes the reduction in the duration of ice during the 20th century to climate change. The BC trends, however, are based on short data records. Most begin during a slightly cooler period – the 1940s and 50s – and end during a warmer period – the 1990s. They are therefore very likely to have been influenced by natural climate variability. If longer records were available, they would probably show slower rates of change in BC.

WHAT CAN WE EXPECT IN FUTURE?

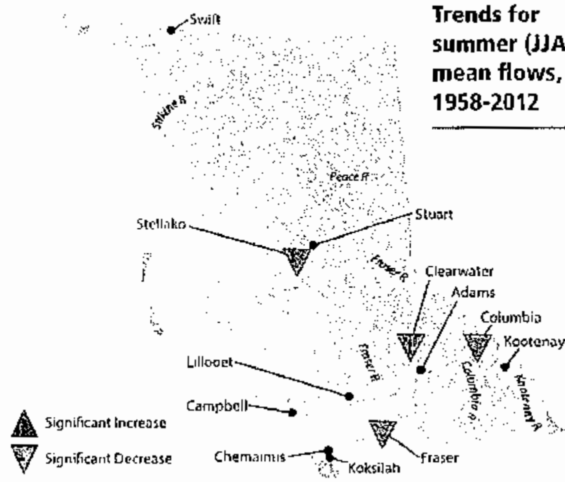
Climate models project that globally, atmospheric warming associated with climate change will continue to be more pronounced in winter and spring than in summer and fall. This warming will likely continue to cause earlier thawing of ice on provincial lakes and rivers.

Revised 2016

Indicators: TIMING AND VOLUME OF RIVER FLOW

Seasonal changes in the timing and volume of river flow have occurred in several locations. The bulk of water flow is occurring earlier in the year on average. At many locations, river flow has decreased in late summer and early fall. This could contribute to water shortages for humans and ecosystems.

Trends for summer (JJA) mean flows, 1958-2012



June, July, August (JJA) mean flow trends between 1958 and 2012. SOURCE: Data from the Water Survey of Canada, Environment and Climate Change Canada (1958-2012). Station list see Appendix C. Analysis by PCIC for Ministry of Environment, 2016.

ABOUT THE INDICATORS

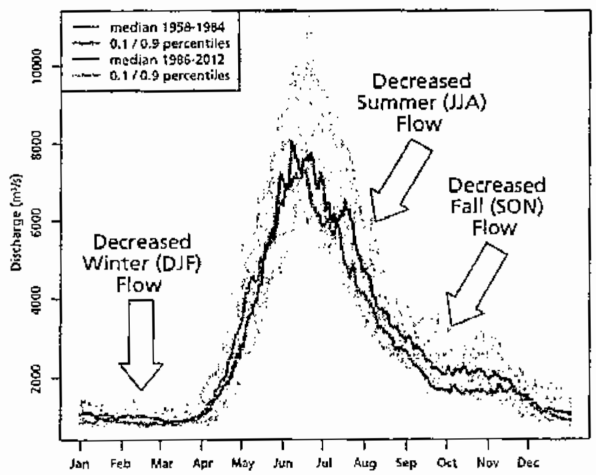
The indicators measure changes in the timing as well as volume of water. Timing is quantified as trends in the dates by which one-half of the total annual volume of each river has passed. Volume changes are quantified by trends in seasonal minimum, maximum, and mean flows. To better assess trends in rivers for more of the province, and for rivers that are rainfall- or snowmelt-fed, daily river flow measurements were analyzed for basins across the province over a 55-year period from 1958 to 2012. In some places it was also possible to analyze a 101-year period from 1912 to 2012.

TRENDS IN RIVER FLOW IN BC

Long-term records are available for five sub-basins of the Fraser River watershed (Adams, Stellako, Stuart, Lillooet, and Clearwater) and the Fraser River at Hope, which drains roughly a quarter of the province. At the Stellako and Fraser at Hope, the date when half the annual water volume has passed advanced nine and six days respectively over 1912 to 2012, while in the Adams the date became seven days later over the 101-year record. Minimum daily flow increased at four of the six sites which, for the Fraser River watershed and its sub-basins, occurs in late winter prior to the onset of spring melt. Three sites demonstrated significant decreases in mean summer (June, July and August) flow, ranging from a 16% to 40% decrease and two sites (Stellako and Lillooet) had significant decreases in minimum flow in late summer (July, August, and September) by 31% and 39%, respectively. Annual minimum, late spring maximum, and spring mean showed increased flow for some sites. All other indicators showed declining trends.

Data was available at stations on the Chemainus, Koksilah, Stellako, Stuart, Clearwater, Adams, Fraser, Lillooet, Columbia, Kootenay, and Swift for the more recent 1958 to 2012 record. Of these rivers, the Chemainus and Koksilah are rainfall-fed, while the others are snowmelt-fed. Declines were seen in most metrics for most rivers, reinforcing the pattern found over the 101-year record with fewer stations. Late spring maximum flows (April, May, June) decreased at the Koksilah and Columbia (at Donald) and late summer minimum flows (July, August, September) decreased at four stations (Chemainus, Stellako, Clearwater, and Fraser). Mean summer flow volume (June, July, August) also decreased between 17% and 39% at four stations (Stellako, Clearwater, Fraser,

Changes to Fraser River Flow between 1958 and 2012



Comparison of flow of the Fraser River at Hope for two equal-length time periods, 1958-1984 and 1986-2012, showing median and 10th and 90th percentiles. Seasonal flows have decreased between the first and the second time period during winter (December, January, February), summer (June, July, August), and fall (September, October, November). SOURCE: Data from the Water Survey of Canada, Environment and Climate Change Canada (1958-2012), Fraser River at Hope (08MF005), augmented with data received from Alan Chapman in 2007, which were adjusted for extractions via the Nechako Reservoir. Analysis by PCIC for Ministry of Environment, 2016.

and Columbia). Because summer flow makes up a relatively small proportion of total annual flow, these large percentages have smaller impacts on total annual flows. However, mean annual flow decreased by 16% in the Fraser at Hope, which is important considering the expanse of BC this basin covers. Over this same period, precipitation showed a statistically non-significant decline of 3% (+/-17%) per century. The discrepancy between the declining river flow and modest to no declines in precipitation indicates the influence of rising temperatures over this period. Warmer temperature leads to greater rates of evapotranspiration which reduces water available for streamflow. Maximum daily flow did not change significantly at any of the stations examined, whereas minimum daily flows decreased at two sites (Columbia and Koksilah) and increased at one (Swift River). Over this period, only one indicator at one river showed significant increases in flow; the Swift River's annual minimum flow. All other significant trends show flow reductions. Comparing average daily streamflow for the Fraser River at Hope for two 27-year periods illustrates the type of changes driving seasonal streamflow trends for many stations across BC. Flows are modestly reduced in winter, increased during spring, and strongly decreased during summer and fall in the latter 1986-2012 period versus the earlier 1958-1984 period. These data have been naturalized to correct for water diverted from the Fraser River catchment to the Nechako reservoir, which started in 1958.

WHY IS IT IMPORTANT?

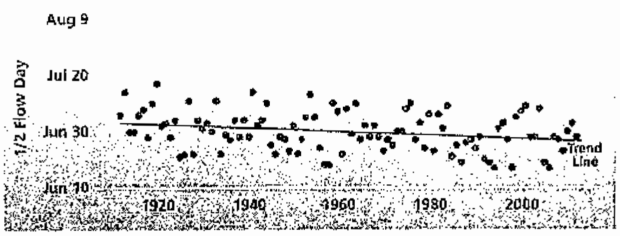
Changes in the timing and volume of flow can affect both natural ecosystems and human communities. Lower flows in summer and later in the season may reduce the amount of water available for agriculture, hydroelectric power generation, industry, and communities in some parts of the BC interior. This is a potentially significant problem in drier areas such as the Okanagan basin, where most streams are already fully allocated to water users and water shortages already exist. Low late-season flows are especially a concern in years when below-average spring and summer rainfall coincides with below-average summer flows. Lower flows are also associated with declining water quality including warmer water temperatures (see "River Temperature") which further threaten the health of aquatic ecosystems and their organisms such as salmon (see "Salmon in the River").

WHY HAS RIVER FLOW CHANGED?

Many factors affect trends in these indicators, such as changes in temperature, precipitation, and evapotranspiration. They also depend on the location, size, elevation, and regime of a basin, be it predominately rainfall- or snowmelt-fed and whether substantial glacier cover exists. Thus, trends in river flow are not uniform over the province for every indicator. Ten of the 11 stations evaluated are part of the Reference Hydrometric Network where direct human influence and land use change have not significantly altered the flow regime over time.

Detecting changes in streamflow and attributing them to the effects humans have had on climate is

Change in Timing of One-half of Fraser River Annual Flow, 1912-2012



The half flow day is defined as the day of the calendar year on which one-half of the total annual water flow has occurred. The solid line indicates that there is a trend at the 5% significance level. Data from the Water Survey of Canada, Environment and Climate Change Canada, augmented with data received from Alan Chapman, adjusted for extractions via the Nechako Reservoir. Analysis by PCIC for Ministry of Environment, 2016. See Appendix C for methodology and references.

more difficult than attributing changes in temperature and precipitation. Soil moisture and runoff changes are difficult to isolate from the difference in precipitation and evaporation alone. Other factors, such as changes in land use, stream management, water withdrawal and varying water use efficiency by plants under different levels of CO_2, also play a role. In BC, snow storage and melting are important to runoff. Winter temperature has increased significantly across the province over the past century leading to less winter precipitation falling as snow and earlier melting of winter snow cover. The earlier passage of the majority of water in snowmelt-fed rivers in the nearby US is detectably different from natural variability since the 1950s and can be attributed to human-caused warming. There is some evidence that declining April 1 Snow Water Equivalent (SWE) in British Columbia has a detectable human influence in simulations that compare human-caused warming with natural variability. This change is consistent with the expected influence of warming on the hydrological cycle. Warming is substantial in a study of the Fraser, Peace, Columbia, and Campbell basins and attributable to human causes. Natural variability alone is not a likely explanation for the observed SWE changes.

WHAT CAN WE EXPECT IN FUTURE?

Future streamflow in the Fraser, Peace, upper Columbia, and Campbell rivers have been investigated up to 2098 using multiple Global Climate Models corrected to match the characteristics of observed temperature and precipitation data for British Columbia. These climate scenarios were used as inputs to a hydrologic model covering 100-gauge sites in the province.

During the 2050s (between 2041 and 2070) in the Fraser River, annual streamflow is projected to increase. Winter and spring flows are projected to increase, summer flows to decrease and smaller changes, in either direction, are projected in the fall. Mean annual peak flow is projected to occur between 5 and 15 days earlier. Most of the trends described above were analyzed for sub-basins of the Fraser River where the majority of long-term records are available over the 101-year period discussed earlier. In the 2050s in the Campbell River, changes in annual streamflow are expected to be negligible, but warmer temperatures in future are expected to result in a significant change in the hydrological regime relative to the 1970s (1961-1990). This watershed is expected to transition from being mixed rainfall- and snowmelt-fed to predominantly rainfall-fed, with increased flow during the winter season and decreased flow in spring and summer. Similar changes have already been observed in other coastal watersheds such as the Chemainus.

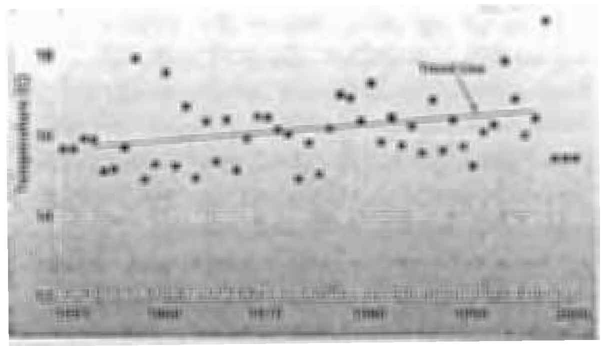
Total annual streamflow is expected to increase for the upper Columbia River for the 2050s, regardless of the model or emissions scenario investigated, but there are important seasonal changes that are expected to occur. Monthly streamflow is expected to increase during the late fall and winter period, the spring melt to occur earlier, and flow to be higher during spring and early summer and lower in late summer and early fall. Annual streamflow is expected to increase for the Peace River for the 2050s, regardless of the model considered. Monthly streamflow projections for the Peace River show consistently higher future discharge during fall and winter. Like the upper Columbia, there is some indication that the Peace River may experience an earlier onset of the spring melt and reductions in streamflow to occur during late summer and early fall. Some of the trends in observed data mimic the projected changes with climate change, suggesting that some effects are underway.

2002 edition

Indicator: RIVER TEMPERATURE

The average summer temperature of the Fraser River has warmed over the past five decades. River warming can have negative impacts on the health, distribution, and survival of salmon but positive impacts on aquatic species that can tolerate warmer water.

Change in Average Fraser River Temperature, 1953-1998



SOURCE: Historical temperature data from the Pacific Salmon Commission, 1941-1998. Historical weather data from Meteorological Service of Canada, Environment Canada 1953-1998. Analysis by John Morrison, Institute of Ocean Sciences, 2001 for the Ministry of Water, Land and Air Protection.
NOTES: Results are statistically significant. ($R^2 = 0.1751$, $p = .0226$).

ABOUT THE INDICATOR

This indicator measures changes in the average summer temperature of the Fraser River at Hell's Gate. It is based on daily measurements of water temperature taken from July 1 to September 15 for the years 1953 to 1998.

TRENDS IN RIVER TEMPERATURE

The temperature of the Fraser River at Hell's Gate in summer warmed during the period 1953 to 1998 at a rate equivalent to 2.2°C per century.

The Fraser River is subject to seasonal and year-to-year variations in temperature that are related to short-term natural climate variability. In general, summer river temperatures are warmer after an El Niño event and cooler after a La Niña event. Because the period of record is only 45 years, these short-term climate variations may have as much influence on the observed trend towards river warming as climate change.

The average temperature of the Columbia River at or near the international boundary during the summers of 1959 to 1997 also appears to have warmed, but the data are not sufficient to establish a trend. In addition, because the Columbia is a highly regulated river system, any apparent trend might be due to human-induced changes in the timing and volume of river flow, or to the temperature and volume of water reservoirs, rather than to climate change.

WHY IS IT IMPORTANT?

The Fraser River flows 1,370 kilometres from its headwaters in the Rocky Mountains to the Pacific Ocean. It supports ecologically important salmon runs, including the majority of Canadian sockeye stocks. Almost all runs must pass through Hell's Gate in their migration upriver to spawn. Warmer river temperatures are expected to affect salmon and other aquatic organisms.

In general, warm water temperatures reduce salmon fitness, survival, and reproductive success and promote potential long-term population declines (see "Salmon in the River"). Declines in Fraser River salmon stocks have negative impacts on provincial fishing and tourism industries and aboriginal and other communities that rely on fish. They affect predators such as bald eagles and bears and coastal ecosystem processes that depend on the nutrients provided by salmon carcasses.

In addition, many provincial salmon stocks are classified as at moderate to high risk of extinction. The United National Intergovernmental Panel on Climate Change (IPCC) believes that, without appropriate management, climate change will lead to changes in freshwater ecosystems that will cause some species currently classified as "critically endangered" to become extinct and the majority of species classified as "endangered" or "vulnerable" to approach extinction in the 21st century.

Over the long term, higher temperatures are expected to result in a shift in the distribution of salmon and other cold-water species to higher latitudes and elevations, together with increased population fragmentation in more southerly parts of their ranges. If other factors were to limit these range shifts, an overall reduction in the distribution of certain species would be the result.

River warming may have positive impacts on aquatic species that can tolerate warmer water temperatures. Native warm-water species may be able to expand their range into higher-altitude lakes and more northerly regions. For example, a 4°C increase in average air temperature is projected to expand the ranges of smallmouth bass and yellow perch northward across Canada by about 500 kilometres. There is also an increased likelihood of successful invasion by non-native species that require warmer water temperatures.

WHY IS RIVER TEMPERATURE INCREASING?

River temperature is the result of complex interactions between the characteristics of the river itself, climate, and adjacent land-use practices.

Many streams and rivers in the Fraser system are snowmelt-fed. In these river systems, climate change is associated with earlier melting of ice in spring, an earlier spring freshet, and lower summer flow volume (see "Timing and Volume of River Flow"). The average summer temperature of the Fraser River is increasing because the average annual temperature is getting warmer and because there is less water in the river to heat. In addition, when snow melts earlier in the season, it reduces the buffering effect of the cold spring freshet on stream temperature in early summer.

Examination of weather records suggests that long-term changes in climate are responsible for 55 percent of the Fraser River warming. During the period studied (1953-1998), summer climate as measured upriver of Hell's Gate at Prince George and Kamloops changed in the following ways: air temperature increased; cloud cover decreased; solar radiation (the amount of sunlight reaching the ground) increased; wind speed decreased; and dew point temperature increased. Each of these changes favours river warming.

Changes in adjacent land use over the record period may also have affected river temperatures. Forestry, agriculture, industrialization, and hydro-electric generation tend to decrease the amount of vegetation cover along rivers and streams, exposing more of the river surface to the sun's heat. The impacts of these events are small, however, in comparison to the impact of climate.

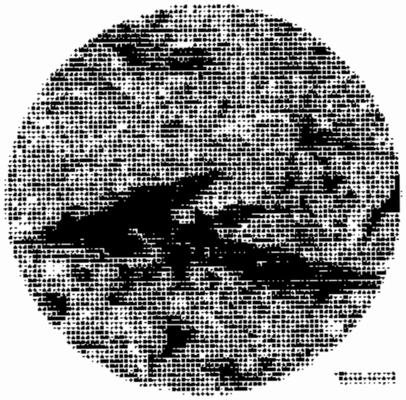
WHAT CAN WE EXPECT IN FUTURE?

River temperatures will continue to vary from one year to the next in response to short-term natural climate variability. If the climate is warming, however, years with warmer river temperatures are expected to occur more frequently. In addition, river temperatures may more often exceed those that are optimal for fish.

Atmospheric temperature and other aspects of climate affect river temperature. Climate models project that air temperatures in British Columbia will increase by 1°C to 4°C from 1961-1990 historical average by the 2080s. The higher rate of warming is projected to occur over the interior – the region of the province that contains most of the rivers and streams that feed the Fraser River system.

2002 edition

SALMON IN THE RIVER

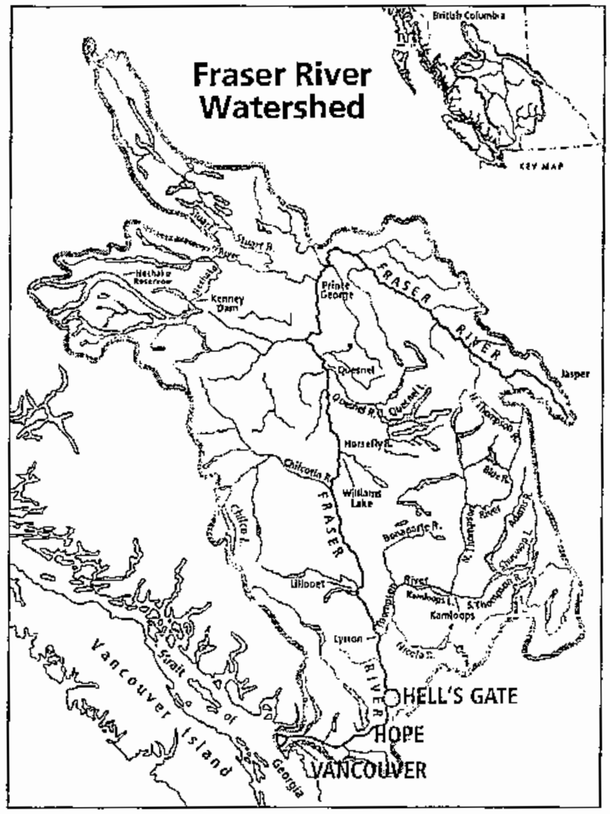


Natural year-to-year variations in river flow and temperature affect the survival of sockeye salmon stocks. Long-term changes in river flow and temperature associated with climate change are therefore likely to have an impact on Fraser River sockeye populations over time.

Fish are sensitive to temperature, which regulates many of their physiological processes. When their environment is warmer, their metabolic rate increases, speeding up internal processes such as oxygen consumption, digestion, and mobility.

Salmon tolerate temperatures of up to about 24.5°C but prefer temperatures from 12°C to 15°C. Because sockeye prefer colder temperatures than other salmon species, sockeye may be the species that is most sensitive to climate change. Temperatures above 15°C can cause stress in sockeye, depleting their energy reserves, making them more susceptible to disease and reducing their capacity to produce viable eggs and sperm. Temperatures above 18°C can impair their swimming ability. They can die from several days' exposure to temperatures between 22°C and 24°C or from brief exposure to temperatures above 24°C.

> Warmer river temperatures are associated with increased mortality in migrating salmon stocks. Changes in river flow and temperature linked to climate change are expected to have profound negative impacts on some salmon stocks.



Fraser River Watershed

SOURCE: Ocean Science and Productivity, Fisheries and Oceans Canada.

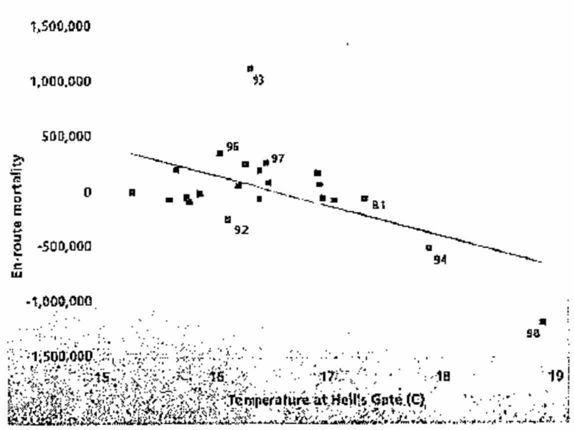
Each summer and fall, adult sockeye return from the ocean to spawn in more than 150 natal stream, river, and lake spawning areas in the Fraser River water-shed. Different stocks start their long swim upriver at different times. The summer run group, including stocks that originate in the Quesnel and Chilko rivers, starts its migration upriver in late July and August. The late run group, including Shuswap stocks, arrives at the mouth of the Fraser River in August, but typically waits four to six weeks before entering the river to start migration.

HOW DOES RIVER TEMPERATURE AFFECT SOCKEYE SALMON?

Most Fraser River sockeye stocks must pass through Hell's Gate, above Hope, in their migration upriver. Measurements taken at Hell's Gate show considerable year-to-year variability in river flow and temperature.

Research has established a link between water flow and temperature and mortality in Fraser River spawning stocks. Fish may die while in transit up the river ("en route mortality") or they may not spawn when they arrive at their spawning grounds ("pre-spawning mortality").

In several years during the past decade, en route mortality in several runs has been greater than 50 percent. Records from 1978 to 1998 indicate that en route losses have been greatest in years with warm river temperatures. The connection is particularly strong in the summer run group, which migrates when river temperatures are at their highest. In recent years the late run group has been starting migration early and is therefore also at risk.



Migration Success of Summer Run Sockeye and Temperature at Hell's Gate, 1978-1998.

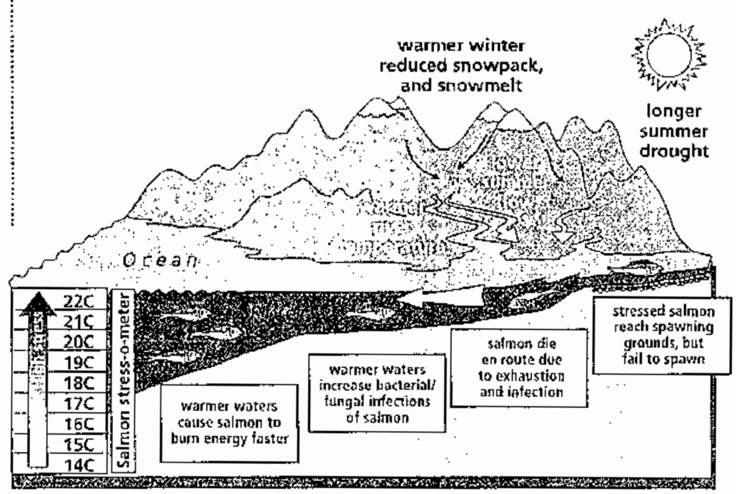
SOURCE: Data and analysis by S. Macdonald and J. Grout, Fisheries and Oceans Canada, 2001. NOTES: En route mortality is the difference between estimates of the number of fish entering the Fraser River, and the number reaching the spawning grounds. A negative number represents fish lost en route. A positive number represents uncertainties in estimation, and/or en route fishing activities. Results are statistically significant at the 95% level.

Pre-spawning mortality across all Fraser River sockeye stocks over a five-decade period ranged from 0 to 85 percent. Studies suggest a weak link between higher rates of pre-spawning mortality and warmer-than-average river temperatures.

Long-term trends in river flow and temperature associated with climate change are therefore reasons to be concerned about the prospects for many Fraser River salmon stocks. Records show that the Fraser River is now discharging more of its annual volume earlier in the year (see "River Flow and Timing"). Earlier spring runoff is associated with lower summer flows and higher water temperatures (see "River Temperature").

WHAT CAN WE EXPECT IN FUTURE?

While river flow and temperature will still vary from one year to the next, summers with lower flow and warmer temperatures will likely occur more often in the future. This is expected to have profound negative impacts on Fraser River sockeye stocks over the long term. More research is needed to determine whether stocks in more northerly rivers – the Skeena, Nass, and Somass – and the Rivers Inlet and Smith Inlet areas will experience the same temperature extremes and will face the same threats as a result of climate change.

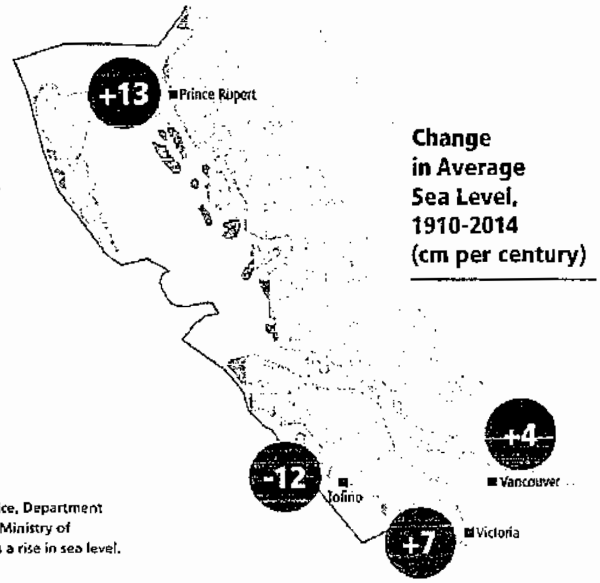


SOURCE: Burghner, R.L. 1991. Life History of Sockeye Salmon. In Pacific Salmon Life Histories. University of British Columbia, p.3-117. Graphic from Temperature Rising: Climate Change in Southwestern British Columbia, 1999.

Revised 2016

Indicator: SEA LEVEL

Average sea level has risen along most of the BC coast over the past century. Higher sea levels increase the risk of flooding of low-lying coastal areas, may contribute to increased erosion of coastlines, and may damage coastal ecosystems and infrastructure.



SOURCE: Data from the Canadian Hydrographic Service, Department of Fisheries and Oceans Canada. Analysis by PCIC for Ministry of Environment, 2016. NOTES: A positive trend indicates a rise in sea level.

ABOUT THE INDICATOR

This indicator measures changes in the average level of the sea relative to the adjacent land. It is based on records from 1910-2014 (with some gaps) from four tide gauges that monitor water levels, located along the British Columbia coast.

The trends identified for coastal BC reflect the combined impacts of climate change and vertical land movements caused by geological processes. The coast of BC is still rising from a process called post-glacial rebound, which refers to the rising of land due to past thinning and retreat of the massive ice sheet that once covered much of the province. In addition, the shifting of tectonic plates generates vertical land motion in coastal BC that is causing parts of Vancouver Island to rise.

SEA LEVEL TRENDS

Average relative sea level rose at the rate of 13.3 centimetres per century at Prince Rupert, 6.6 centimetres at Victoria, and 3.7 centimetres at Vancouver. In contrast, relative sea level fell at Tofino at the rate of 12.4 centimetres per century. These trends reflect the combined impacts of vertical movements of the shoreline and a rise in average global sea level.

The variation in sea level change between the four sites is largely explained by different amounts of vertical land motion. The southwest coast of Vancouver Island is rising at about 25 centimetres per century, while the vertical land motion of Prince Rupert is negligible, thus explaining the approximately 25 centimetres difference in sea-level change between Tofino and Prince Rupert.

Tide gauge measurements from around the world suggest that global sea level rose about 1.7 millimetres per year (17 centimetres per century) on average during the 20th century. Over the past two decades, tide gauge and satellite measurements indicate that the rate of global sea-level rise has increased to about 3.2 millimetres per year (32 centimetres per century).

WHY IS IT IMPORTANT?

Rising sea level will likely contribute to increased flooding of low-lying coastal areas. This may threaten wetlands, beaches, dunes, and other sensitive coastal ecosystems, and sites of cultural importance to Aboriginal peoples. It may also strain drainage and sewage systems in some coastal communities. Salt water may intrude into groundwater aquifers, making the water they contain unfit for household

Coastal Regions at Risk

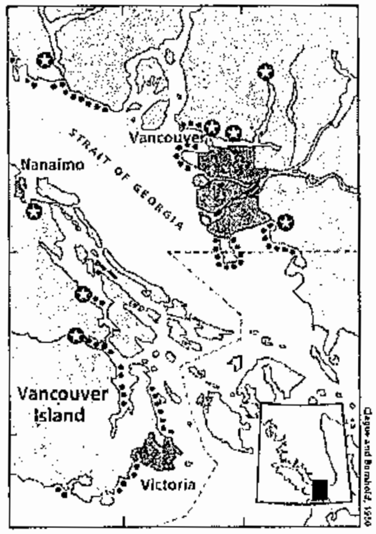
LEGEND

Shoreline vulnerable to erosion

Fraser River delta

Other low-lying areas

SOURCE: Clague and Bornhold. 1980. Graphic from Temperature Rising, 1999.



or agricultural use. Even before they are actually inundated, low-lying agricultural lands may become too saline for cultivation.

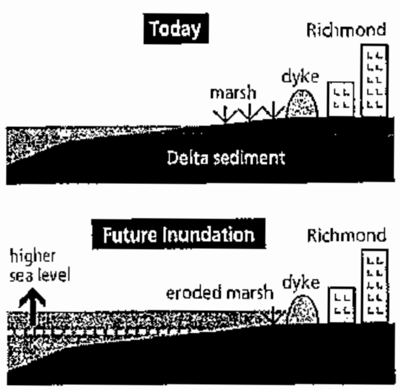
Higher mean sea level and more frequent extreme high-water events, such as king tides, will increase the likelihood that storms will damage waterfront homes, wharves, roads, and port facilities and contribute to coastal erosion.

Areas particularly at risk are the Fraser River delta, where 100 square kilometres of land are currently within one metre of sea level, and Prince Rupert, which experiences extreme high water events more frequently than other areas of the coast.

Changes in the height and direction of prevailing ocean waves, storm waves, and storm surges as a result of climate change may also have serious impacts on some coastal areas.

Shoreline Inundation

SOURCE: Clague J.J. and B.D. Bornhold. 1980. Morphology and littoral processes of the Pacific Coast of Canada. In The Coastline of Canada; Littoral Processes and Shore Morphology; Geol. Survey of Canada Paper 80-10, p.339-380. Graphic from Temperature Rising, 1999.



WHY IS SEA LEVEL RISING?

The rise in average global sea level observed during the 20th century is very likely due to climate change. As the atmosphere warms, sea water warms and expands in volume. Thermal expansion is a major influence on past changes in sea level. It is expected to make the greatest contribution to a rising sea level over the next century.

Sea level also changes when the overall volume of water in the ocean increases or decreases. As glaciers, ice caps, and ice sheets lose mass from melting and calving, water previously stored on land as ice and snow is added to the ocean. This additional water is expected to contribute substantially to a rise in global sea level over the next century.

Processes not related to climate change also influence relative sea level. These include vertical movements of the land and short-term natural changes in ocean temperature and circulation patterns. For example, El Niño events can cause water levels to increase by a few tens of centimetres in winter months.

WHAT CAN WE EXPECT IN FUTURE?

Climate models project a further rise in global mean sea level of 26 to 98 centimetres by 2100. The rate and magnitude of this rise in sea level will not be uniform over the globe. It will vary from one basin to another, reflecting variations in the amount of ocean warming and the way in which ocean currents redistribute heat and mass.

In most areas, climate change is expected to produce mean and extreme water levels higher than any yet recorded. Where relative sea level is projected to rise, extreme high water levels are expected to occur with increasing frequency.

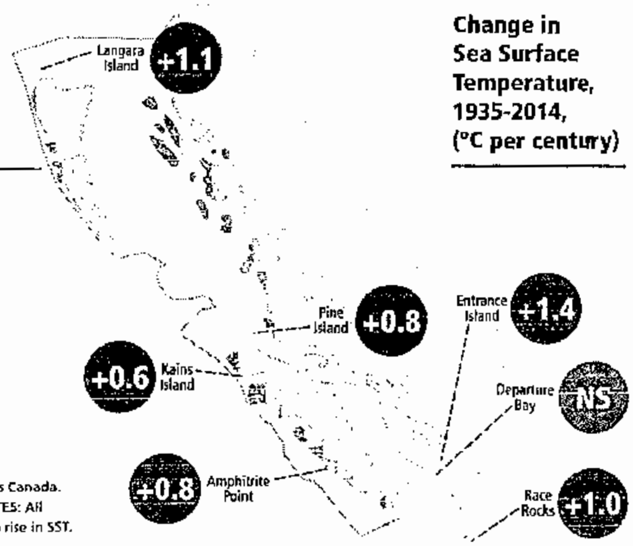
Sea level is expected to continue to rise, even if greenhouse gas concentrations in the atmosphere stabilize. The deep ocean responds slowly to climate change, and thermal expansion of the ocean is likely to continue for hundreds of years. As well, ice masses (glaciers, ice caps, and ice sheets) are expected to continue to shrink with the melted ice increasing the volume of water in the ocean.

Revised 2016

Indicators: SEA SURFACE TEMPERATURE

Sea surface temperature in BC's coastal waters increased during the 20th century. Higher temperatures are associated with reduced ocean productivity and potential adverse impacts on marine resources and the human communities that depend on them.

Change in Sea Surface Temperature, 1935-2014, (°C per century)



SOURCE: Data from Department of Fisheries and Oceans Canada. Analysis by PCIC for Ministry of Environment, 2016. NOTES: All statistically significant trends are positive and indicate a rise in SST.

ABOUT THE INDICATORS

Sea surface temperature is measured manually at light stations along the BC coastline. Measurements are taken at the first daily high tide using a collection bucket and thermometers. Of the 19 stations with sea surface temperature records, only seven have a sufficient record for long-term analysis. Trends were calculated on data from the years 1935 through 2014 on a seasonal and annual basis.

SEA SURFACE TRENDS IN BRITISH COLUMBIA

Annual average sea surface temperatures have warmed significantly between 1935 and 2014 at all stations examined. Seasonal sea surface temperatures have warmed significantly at some stations and seasons and not significantly for others. For fall and winter, only three of the seven stations report a statistically significant trend (Entrance Island near Nanaimo, Langara Island off the NW coast of Haida Gwaii, and Race Rocks in the Strait of Juan de Fuca west of Victoria). Warming trends increase in spring and are strongest in summer. In spring, four stations reported significant trends (Amphitrite Point on the west coast of Vancouver Island near Ucluelet, Entrance Island, Pine Island off the northeast coast of Vancouver Island, and Race Rocks south of Victoria). In summer, five stations show significant warming (Amphitrite Point, Entrance Island, Kains Island off the northwest coast of Vancouver Island, Pine Island, and Race Rocks). Only Entrance Island and Race Rocks stations show seasonal trends that are significant in all seasons.

The results show seasonal warming trends from a low of 0.7°C per century for Race Rocks' winter trend to a high of 2.2°C per century for Entrance Island's summer trend. Trends in annual average temperature vary substantially from a low of 0.6°C per century for Kains Island, to a high of 1.4°C per century for Entrance Island. The lack of trends for any season at Departure Bay contrasts with results from other stations that reveal a significant trend in at least one season of the year. Departure Bay is in a location of limited tidal mixing and strong influences from nearby freshwater outfalls. Other nearby stations, such as Entrance Island, are more exposed to the Strait of Georgia where substantial tidal mixing and exposure to Fraser River waters occurs that minimize other local effects. These results differ slightly from published period of record analysis of annual trends. This is discussed in the report's appendix.

The Intergovernmental Panel on Climate Change (IPCC) suggests that average global sea surface temperature has increased at a rate of 1.1°C per century between 1971 and 2010. The rate of warming along the west coast of Vancouver Island – the coastal area most exposed to trends in the Pacific Ocean – is similar to the global average.

WHY IS IT IMPORTANT?

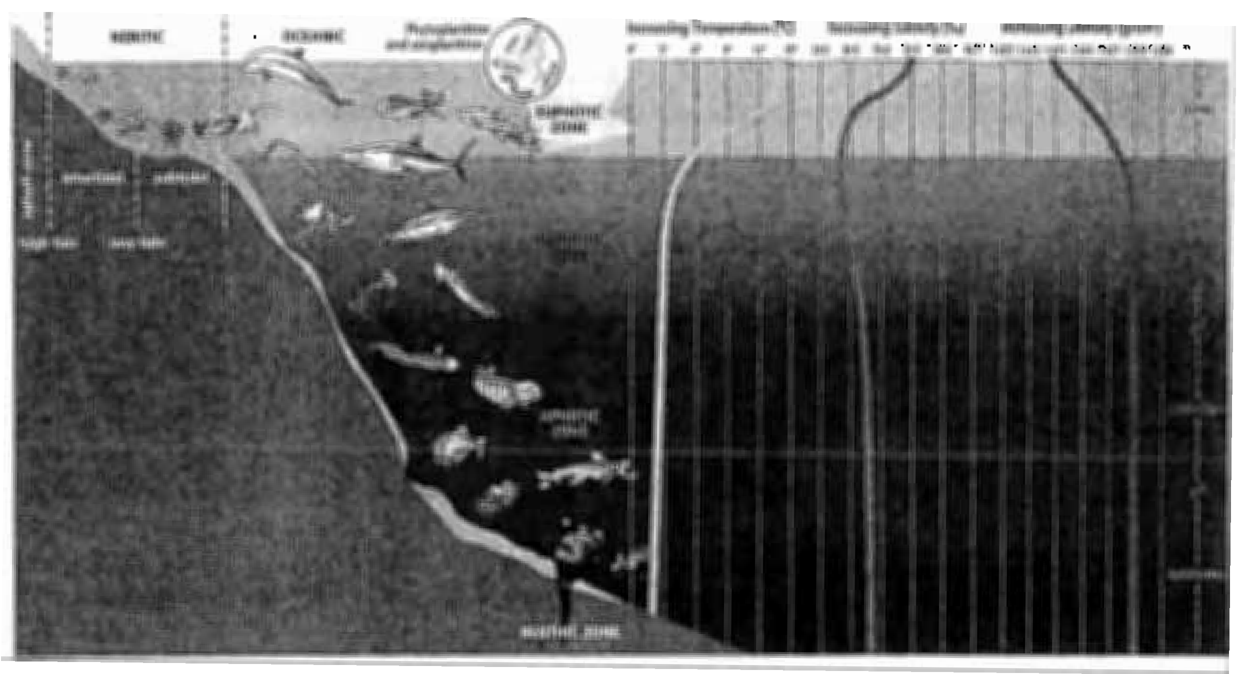
Ocean temperature, salinity, and density are important measures of marine ecosystem health and productivity. Long-term changes in one or more of these measures are likely to affect marine species and ecosystems and the human communities and resource industries that depend on the sea.

Higher sea surface temperatures are linked to changes in salmon distribution and migration patterns and subsequent potential declines in reproductive success (see "Salmon at Sea"). They are also associated with reduced availability of food for and declines in seabird populations (see "Seabird Survival"). In addition, sea temperature is important because it affects the stability of the water column, which in turn affects ocean productivity via nutrient supply.

The upper 100 metres or so is the most biologically productive part of the ocean. In this zone, sunlight drives photosynthesis, supporting the growth of microscopic plants. These phytoplankton become food for microscopic animals – or zooplankton – that in turn support fish and other marine animals.

In spring and summer, as phytoplankton populations grow, they use up nutrients in the upper layer of the ocean. These nutrients are typically replaced in the fall through mixing processes that bring mineral-rich water from the ocean depths to the surface. Such mixing is the result of waves, storms, tides, and prevailing winds. The deeper the mixing, the more nutrients rise to the surface, and the greater the productivity of the ocean the following year.

Temperature affects the stability of the water column and therefore the depth to which mixing can



Ocean light zones and generalized temperature, salinity, and density-depth profile for ocean water.
SOURCE: Adapted from Windows to the Universe, University Corporation for Atmospheric Research (UCAR), 2004.

occur. Temperature and salinity in the deep Pacific Ocean are stable on decade to century timescales. The sea surface is typically warmer, less saline, and less dense than the deeper water and therefore tends to "float" on top of the deeper, denser water. When the sea surface is warmer than usual, the difference in density between the surface and deeper water is greater, the surface sits more securely on top of the deeper water, and mixing becomes more difficult.

Natural cycles of climate variability are associated with cycles in ocean productivity. In an El Niño year, the sea surface near the BC coast is warmer than usual in summer, and the upper water column is more stable. Mixing may therefore occur to a depth of only 100 metres. In a La Niña year, the sea surface in summer is cooler than usual, and the water column is less stable. Mixing may occur down to 140 metres, which results in greater ocean productivity.

The trends towards warmer temperatures may lead to a more stable ocean near our coast, which would reduce nutrient supply and be of great concern.

WHY IS THE SEA SURFACE CHANGING?

The ocean is an integral and responsive component of the climate system. At its surface, it exchanges heat, water (through evaporation and precipitation), and carbon dioxide and other gases with the atmosphere. The 20th century trend towards higher sea surface temperatures is related to increasing atmospheric temperatures and is symptomatic of the warming ocean, including its interior. It is estimated that more than 90% of the increase in heat energy stored by the climate system as a result of increased GHGs is stored in the ocean.

Of BC's three regions of coastal waters, the west coast of Vancouver Island is the most exposed to the Pacific Ocean and the most likely to reflect oceanic trends. In the other two regions (Georgia Basin and Queen Charlotte Sound), local evaporation and precipitation rates and freshwater runoff from rivers and streams may affect temperature.

WHAT CAN WE EXPECT IN FUTURE?

Sea surface temperature will likely continue to vary from year to year and from decade to decade in response to natural cycles. Climate models project, however, that the Earth will continue to warm and that average global sea surface temperature will increase by 0.6°C to 2°C in the top 100m by the end of the 21st century. The ocean will warm more slowly than the land. Current models do not yet allow scientists to project with confidence the future frequency, amplitude, and spatial pattern of El Niño events.

2002 edition

SALMON AT SEA

old

Natural variations in sea surface temperature are associated with changes in the distribution and survival of sockeye salmon. As a result, the effect of climate change on long-term increases in average ocean temperature is likely to have an impact on sockeye populations over time.

Salmon and other fish are cold-blooded, and the temperature of their environment regulates many of their physiological processes. Warmer water temperatures raise their metabolic rate and speed up movement and internal processes such as growth, oxygen consumption, and digestion.

Studies suggest that salmon prefer a temperature very close to the temperature that promotes optimal growth. When food is abundant, they can afford – from a biological perspective – to stay in warmer waters. The abundance of food makes up for the higher requirements needed to fuel a more active metabolism. When food is limited, however, fish move into cooler waters, where they need less food to grow and survive.

The temperature range that fish prefer is species-specific. In general, salmon like cold water, and sockeye prefer colder water than other salmon species. For this reason, sockeye may be the salmon species most sensitive to climate change. Fraser River sockeye stocks are of particular concern because they are already close to the southern boundary of the range for sockeye and are thus more likely than other sockeye stocks to be exposed to water temperatures outside their preferred range.

Most Fraser River sockeye stocks enter the ocean as smolts in the spring and spend a few weeks in the Strait of Georgia before migrating northwards along the coast of British Columbia to Alaska in early summer. During this migration, they stay on the continental shelf – a relatively shallow zone extending 20 to 30 kilometres offshore. In late autumn and winter, after reaching the Aleutian Islands, they move southwards into the open ocean. They spend one to three years at sea before they return as adults to the Fraser River in late summer and swim upstream to spawn and die.

HOW DOES SEA TEMPERATURE AFFECT SOCKEYE SALMON?

The sea surface is subject to natural cycles of warming and cooling and corresponding periods of lower and higher ocean productivity (see "Sea Surface Temperature"). These cycles are associated with year-to-year variability in sockeye production. Warmer sea surface temperatures are associated with increased juvenile sockeye mortality, changes in ocean distribution, changes in the timing of migrations, and smaller returning adult fish.

> For sockeye salmon, warm years are associated with increased juvenile mortality, reduced distribution, increased competition, and reduced spawning success.

During warm years, ocean productivity is relatively low and may result in slower growth in juvenile salmon, making them vulnerable to predation for a longer period of time. In addition, subtropical fish such as mackerel migrate northwards during warm years and can compete for food with, or prey upon, young salmon in coastal waters.

Some researchers have associated increasing sea surface temperatures with a decrease in the habitable area for sockeye in the North Pacific. During their years in the open ocean, sockeye undertake extensive migrations within a region bounded by the Bering Sea in the north and 40°N latitude in the south. Within this region, the area used by sockeye varies by season and is closely associated with water temperature. The southern limit of their distribution varies from between the 6°C and 7°C isotherms in winter, to the 9°C isotherm in spring and early summer, and the 13.5°C isotherm in summer. In years when sea surface temperature is higher, the habitable area for sockeye is smaller.

Ocean temperature appears to affect the timing of sockeye migrations from the ocean back to the Fraser River. Evidence suggests that in warm years, sockeye arrive later at the mouth of the river. Salmon that arrive later than normal at the mouth of the river may also arrive late at their spawning grounds. Late spawning can have a negative effect on the time when young salmon emerge the following spring and their subsequent survival.

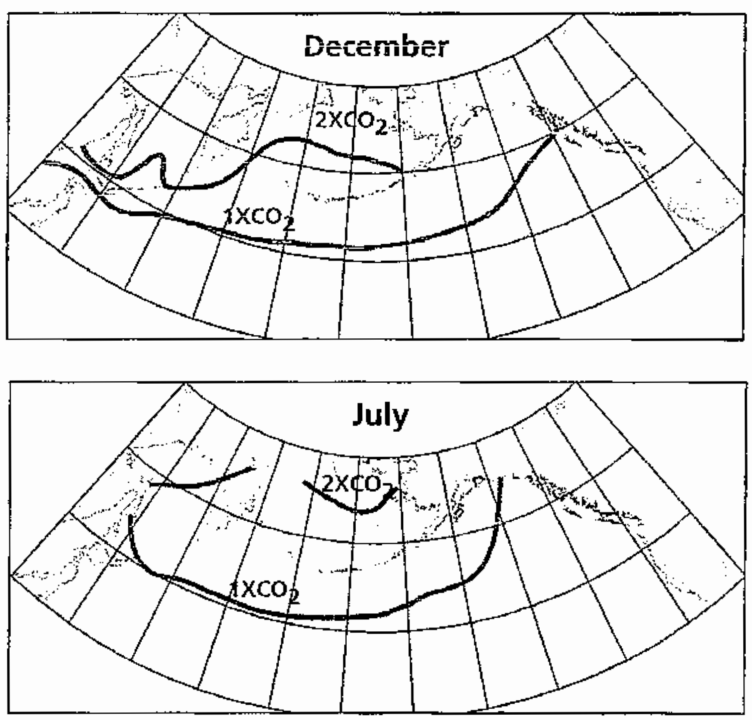
Ocean temperature also appears to affect the size of the returning fish. In warmer years, if fish congregate within a smaller habitable area and compete for the same amount of food, individual growth may be slower, and returning fish may be smaller than normal. In addition, warmer years are associated with reduced ocean productivity and the potential for increased competition for food. In 1997 – a particularly warm year in the northeast Pacific Ocean – returning sockeye were much smaller than normal. Smaller fish may not be able to migrate upstream through the Fraser River system to their spawning grounds as effectively as larger fish.

WHAT CAN WE EXPECT IN FUTURE?

Coastal waters in BC have warmed during the past century, and climate models suggest that ocean warming associated with climate change will continue. While sea surface temperature will still vary from one year to the next, it will be "warm" during proportionally more years. For sockeye, warm years are associated with increased juvenile mortality, restricted distribution, increased competition for food, and reduced spawning success. An increase in the proportion of warm years can therefore reasonably be expected to have a profound long-term negative impact on Fraser River sockeye stocks.

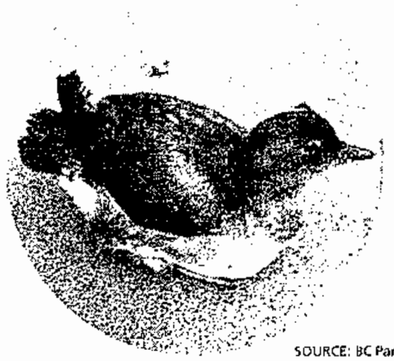
Winter and Summer Distribution of Sockeye Salmon in the Pacific Ocean, Under Current ($1XCO_2$) and Future ($2XCO_2$) Concentrations of Atmospheric CO_2

SOURCE: Welch, D.W., Y. Ishida, and K. Nagasawa. 1998. Thermal Limits and Ocean Migrations of Sockeye Salmon (Oncorhynchus nerka): Long-Term Consequences of Global Warming. Can. J. Fish. Aquat. Sci. 55:937-948.
NOTES: $1XCO_2$ refers to the current atmospheric concentration of CO_2. $2XCO_2$ refers to the doubling of atmospheric CO_2 concentration from this baseline. Climate models predict that $2XCO_2$ will occur during the 21st century. As CO_2 concentration increases, atmospheric and ocean temperature increase, and fish move northwards into cooler water.



2002 edition

SEABIRD SURVIVAL



SOURCE: BC Parks

The reproductive success of the Cassin's auklet *(Ptychoramphus aleuticus)* is sensitive to ocean temperature. Increases in sea surface temperature associated with climate change may therefore threaten the long-term survival of this seabird.

The auklet breeds in a few large colonies along the western coast of North America. Triangle Island, an ecological reserve off the northern tip of Vancouver Island, is home to the world's largest colony, consisting of 1.1 million breeding birds.

Some populations of Cassin's auklet have declined in recent years. A colony on the Farallon Islands in California experienced a 65 percent decline between 1972 and 1997. The Triangle Island population declined between 1989 and 1999, and in several years, breeding success was poor. However, a third population that breeds on Frederick Island off the coast of northern British Columbia showed no signs of population decline during the 1990s and has had consistently good breeding success.

Higher ocean temperatures will affect the long-term survival of Cassin's auklet populations in BC because warmer surface water decreases the food supply for developing chicks.

WHY ARE POPULATIONS DECLINING?

The evidence suggests that population declines are linked to a long-term reduction in the availability of zooplankton – a major food source for Cassin's auklet chicks – in the marine ecosystem that extends from California northwards as far as northern Vancouver Island. Research has documented a relationship between warmer spring ocean temperatures, reduced availability of zooplankton, and decreased growth rates and survival of seabird chicks.

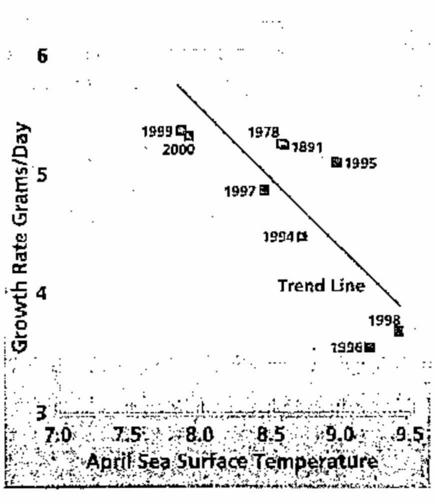
Cassin's auklets attempt to raise a single chick per year, and the survival of each chick is therefore important to the long-term survival of the entire population. Cassin's auklet parents care for their chick for 40 to 60 days after it hatches, feeding it zooplankton – primarily small shrimp-like organisms called copepods. Both parents use their wings to "fly" underwater in search of food for their chick, transporting the food within a throat pouch and regurgitating it for the chick when they get back to the burrow. The growth and survival of Cassin's auklet chicks depend on the availability of copepods in the top 30 metres of the ocean – the depth to which the auklet parents are able to dive.

Copepods inhabit the sea surface for only a brief period during the spring. Their metabolic rate, growth, and development are synchronized with temperature. As surface temperatures warm up, copepod larvae migrate from deep ocean waters to the surface, where they feed on phytoplankton and grow to adult size before returning to the deeper waters of the ocean. When spring surface waters warm earlier in the season, the copepods develop more quickly, become adults faster, and migrate back to deeper waters sooner than they do in years when spring surface waters are cool.

In warm years, the times when seabirds breed and when food is most available are poorly matched. By the time the Cassin's auklet chicks hatch, the copepods are already returning to deeper water, and there is a diminishing food supply for the chicks. As a result, the chicks grow slowly and often starve to death later in the season.

In contrast, when spring surface-water temperatures are cool, the copepods persist longer in the surface waters, so that food is available for chicks throughout the development period, from hatching to the time when they are ready to leave the burrow. The location of Frederick Island explains the health of its Cassin's auklet population. Because the island is so far north, the sea surface temperature during the period when chicks are growing and developing remains cool enough – even in warmer years – to ensure that they have enough food.

Average Growth Rate (grams/day) of Cassin's Auklet Chicks and Sea Surface Temperature near Triangle Island



SOURCE: Original data and analysis from Doug Bertram, Simon Fraser University, Centre for Wildlife Ecology and Canadian Wildlife Service, 2001 for Ministry of Water, Land and Air Protection. NOTES: Average growth rate (grams/day) of Cassin's Auklet chicks is based on weight change between 5 and 25 days from date of hatching. Cassin's Auklet chick growth rates and survival decline as ocean temperature increases (April SST > 7.5°C). The slope of the line is statistically significant ($F_{1,7}=12.5$; $P=0.009$).

Climate change is linked to an increase in average sea surface temperature in waters off the coast of BC. In the 1990s, these temperatures were some of the highest ever observed in the 20th century. In years such as 1996 and 1998, when spring was early and sea surface temperatures were warmer than usual, the growth rates of Cassin's auklet chicks on Triangle Island were much lower than in cooler years such as 1999.

WHAT CAN WE EXPECT IN FUTURE?

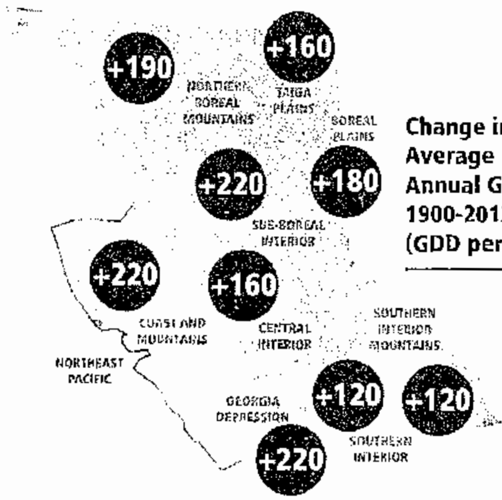
Average global sea surface temperature has increased by 0.4°C to 0.8°C since the late 19th century and is expected to continue to rise during the next century. Populations of Cassin's auklet on Triangle Island are therefore likely to continue to grow slowly, and chick mortality is likely to continue to increase. If the adult birds cannot replace themselves, the population will continue to decline.

The story of the Cassin's auklet is one example of how climate change may affect the distribution and survival of individual species in BC. Many other species – marine, freshwater, and terrestrial – may be similarly affected during the decades to come.

Revised 2015

Indicator: GROWING DEGREE DAYS

The average heat energy available for plant growth and development has increased over the past century, particularly in Coastal BC.



Change in Average Annual GDD 1900-2013 (GDD per century)

SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment Climate Action Secretariat. NOTES: A positive sign indicates an increase in GDD.

ABOUT THE INDICATOR

This indicator measures changes in the amount of heat energy available for plant growth, expressed in units called Growing Degree Days (GDD).

Assessment of annual GDD is based on available temperature records from 1900 to 2013.

GDD TRENDS IN BRITISH COLUMBIA

Annual Growing Degree Days increased from 1900 to 2013 across the province. On average there are 190 more GDD in BC than at the beginning of the 20th century. These trends are consistent with trends over the past century toward higher average annual temperatures across British Columbia.

The greatest increase in GDD has occurred on the coast. The Coast and Mountains and Georgia Depression ecoprovinces have both experienced an increase in energy available for plant growth of 220 GDD per century. Heat energy has increased in the Sub-Boreal Interior ecoprovince by 220 GDD per century as well. The annual trend in both the Southern Interior and Southern Interior Mountains ecoprovinces is an increase of 120 GDD per century. In the north of BC (Boreal Plains, Taiga Plains, and Northern Boreal Mountains) annual average heat energy has increased by 160 to 190 GDD per century.

WHY IS IT IMPORTANT?

Plants and invertebrates require a certain amount of heat to develop from one stage in their life cycle to another. The measure of accumulated heat is known as "physiological time" and is measured in units called "degree days." All individuals of the same species require the same number of degree days to develop from one life stage to another. When temperatures are warmer, they develop faster.

Each plant species – and each insect species – has its own minimum temperature requirement for growth. For example, spinach can grow when average daily temperatures are as low as 2.2°C, while corn requires temperatures of at least 10°C.

Because of these differences, agrologists sometimes refer to an average minimum temperature of 5°C when they talk about the heat requirements of agricultural plants as a group. For the typical agricultural plant, GDD for one day is calculated as the difference between the average temperature and 5°C. For example, a day when the average temperature is 12°C contributes 7 GDD to the

Heat requirements of Agricultural Crop and Pest Species

Species	Minimum Threshold	Degree Day Requirements (over threshold temperature)
Sweet corn	10C	855
Thompson grape	10C	1600-1800
Codling moth	11C	590
Pea aphid	5.5C	118

annual total number of GDDs for that location. GDD is calculated for only those days when the average temperature is higher than 5°C.

A significant increase in available heat energy could allow farmers to introduce new varieties of crops that were previously marginal or not viable in their regions. If adequate soil moisture, soil fertility and light are also available, this could allow agriculture to expand to new regions and sites within the province.

Some of the other impacts of climate change could have negative impacts on agriculture. Changes in hydrological systems combined with warmer temperatures and greater evapotranspiration, for example, may mean less available soil moisture in some regions. And warmer temperatures may also mean that new insect pest species are able to move into a region. Further, warmer temperatures may threaten crops that are not tolerant of extreme warm temperatures above certain fixed thresholds that reflect the crop's physiology.

WHY IS GDD INCREASING?

From 1900 to 2013 average annual temperatures warmed in BC at a rate of 1.4°C per century. Because GDD is related to average daily temperature, it is not surprising that the amount of energy available for plant growth and development has also increased.

WHAT CAN WE EXPECT IN FUTURE?

Climate models indicate that temperatures will continue to rise in BC by 1.7°C to 4.5°C by the 2080s. The higher rate of warming is projected to occur over the interior of the province. Annual GDD should continue to increase as the climate continues to warm.

The United Nations Intergovernmental Panel on Climate Change (IPCC) suggests, however, that increases in average annual temperature of more than a few degrees centigrade will result in a general reduction, with some variation, in potential crop yields in mid-latitudes.

2002 edition

MOUNTAIN PINE BEETLE RANGE

SOURCE: Canadian Forest Service

The mountain pine beetle is a native insect with an important role in maintaining many pine ecosystems. It is also the most important forest pest in western Canada and has killed an estimated 300 million trees in British Columbia over the last 20 years and damaged timber worth an estimated six billion dollars.

While mountain pine beetle will attack most western pines, its primary host throughout most of its range is lodgepole pine. Mountain pine beetles burrow into the bark of the host tree and lay their eggs there in summer. The eggs hatch inside the tree and larvae remain there over the winter. During the following spring, larvae complete their development. Burrowing and feeding activities of the larvae create networks of channels known as galleries beneath the bark, causing the death of the tree.

Adult beetles emerge from their host tree in mid- to late summer and disperse in search of new trees to colonize. Dispersal may be within the same stand or over distances of 100 kilometres or more. Once the beetles find a new host tree, mated females bore through the bark to lay their eggs, starting a new cycle.

> Temperature limits the range and size of mountain pine beetle populations. Warmer temperatures may allow the beetles to move northwards into new regions and upwards into new ecosystems.

Endemic populations of mountain pine beetle are common throughout lodgepole pine forests. They tend to inhabit individual trees dispersed throughout a stand that are weaker and less resistant to invasion. In these endemic populations, births and deaths are in balance. Predators, disease, and competition for food and space control population size. The capacity of most healthy trees to resist a normal beetle attack also helps control the beetle population.

Mountain pine beetle populations increase from time to time within a stand when conditions allow – for example, when trees are stressed by crowding, flooding, or root disease. Such stand-level infestations can quickly become a full-scale outbreak under ideal conditions, with beetles invading – and ultimately killing – many trees across the forest landscape. Periodic mountain pine beetle outbreaks like this created ideal conditions for fire, which has historically played a vital role in maintaining native pine ecosystems by eliminating competing vegetation, preparing the seedbed, and releasing seeds from cones, which require heat to open.

HOW DOES TEMPERATURE AFFECT MOUNTAIN PINE BEETLES?

Temperature is one of the primary sources of mortality for mountain pine beetles.

When temperatures in the summer and fall are warm enough, larvae hatch and grow adequately before the onset of winter. When they are at the late larval stage, mountain pine beetles are resistant to cold and can withstand temperatures close to -40°C for long periods of time.

When temperatures in the summer and fall are relatively cool, however, the larvae grow more slowly and may not reach the ideal life stage before winter. As a result, many will die. For this reason, the mountain pine beetle cannot establish populations at high elevations or at northern latitudes. Its distribution is bounded by the -40°C isotherm, which joins sites where the average of the lowest temperature recorded each year (1921-1950) is -40°C.

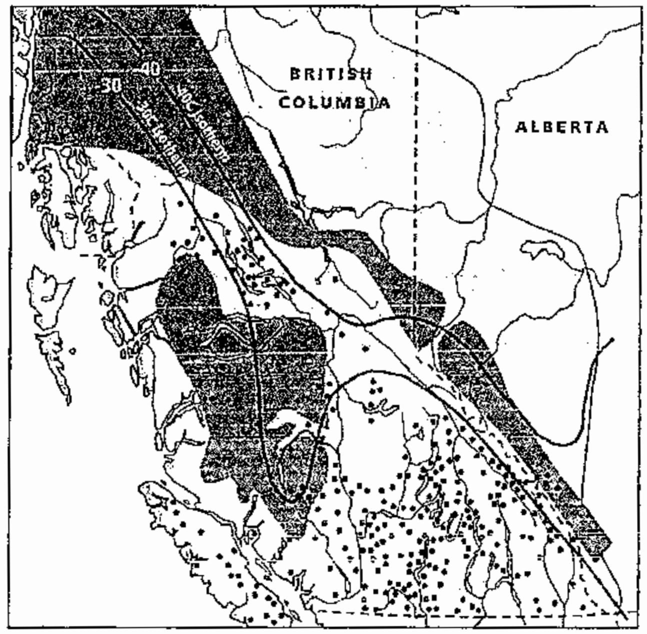
Lodgepole pine ecosystems – the preferred forest of the mountain pine beetle – extend north into the Yukon and the Northwest Territories and east into Alberta. Climate limitations currently prevent the mountain pine beetle from establishing itself in these regions. Warmer temperatures, in particular warmer winter temperatures associated with climate change, may allow the mountain pine beetle to extend its range northwards and eastwards into these ecosystems. With warming, regions that are currently too cold for the mountain pine beetle will become more suitable.

A 2.5°C increase in temperature would likely shift the northern boundary of the region suitable for the mountain pine beetle a further 7 degrees of latitude north. A range expansion of this size would allow beetles potential access to formerly unoccupied lodgepole pine habitat. It would also give them the potential to invade jack pine forests, a major component of the boreal forest that is currently free of beetles.

Warmer winter temperatures may also allow the mountain pine beetle to extend its range upwards into high-elevation pine forests – for example, whitebark and limber pine forests in southeastern BC – that are not adapted to the beetle's impacts.

An additional concern is the possibility that climate change may allow mountain pine beetle infestations and outbreaks to occur more regularly and with greater severity within the beetle's current range. At present, mountain pine beetle outbreaks in BC are limited to the southern portion of the province. Outbreaks occur almost exclusively in regions where it is warm enough for mountain pine beetles to complete their development within a year. In such regions, when weather conditions are warmer than usual, a large number of larvae can survive the winter. Larger populations of adult beetles can more easily overcome the resistance of healthy trees, allowing the development of stand-level infestations and of outbreaks. Consequently, it is highly possible that an increase in winter temperatures associated with climate change could increase the potential for outbreaks.

Distribution of Mountain Pine Beetle Infestations, 1910-1970



LEGEND

- Areas where there is not enough accumulated heat for beetles to complete development on a one-year cycle. (i.e. average degree-day accumulation <833 above 5.6C)
- Range of lodgepole pine
- Recorded MPB infestations 1910-1970

SOURCE: A. Carroll, Pacific Forestry Centre, 2001. Adapted from Safranyik. L. 1990. Temperature and insect interactions in western North America. Proceedings of the Society of American Foresters National Convention. Washington DC. SAF Publication 90-02. pp. 166-170. Isotherms from Department of Mines and Technical Surveys. 1957. Atlas of Canada.

WHAT CAN WE EXPECT IN FUTURE?

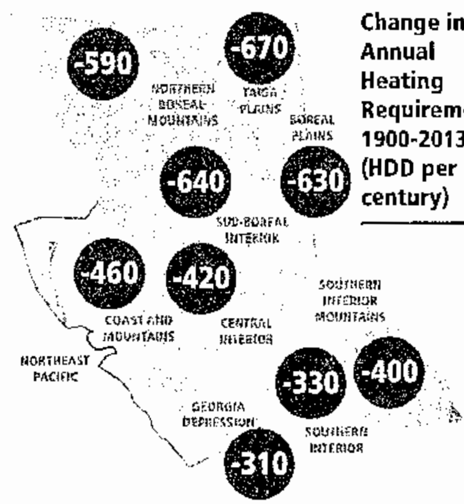
Monitoring indicates that average temperatures over most of British Columbia warmed during the past century, with the greatest increases occurring in the north. Climate models project that this warming trend will continue. Most importantly, the data show that minimum temperatures have warmed during this time period.

Because minimum temperatures delineate the northern range of the mountain pine beetle, this increase in minimum temperatures provides forest managers with reason for concern.

Revised 2015

Indicators: HEATING AND COOLING REQUIREMENTS

Throughout BC, but especially in the north, the amount of energy required for heating similarly constructed and insulated buildings decreased during the past century. The amount of energy required for cooling increased the most in southern BC.



Change in Annual Heating Requirements, 1900-2013, (HDD per century)

SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment. NOTES: A negative sign indicates a decrease in heating requirements.

ABOUT THE INDICATORS

These indicators measure changes in the annual energy requirements for heating and cooling. The figures in this section show the average rate of change in annual Heating Degree Days and Cooling Degree Days over a century for all the ecoprovinces in BC. The trends are based on temperature records from 1900 to 2013 from weather observation stations throughout the province.

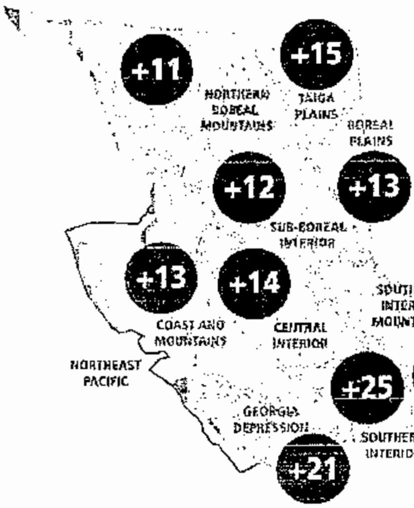
Heating requirements are measured in units called Heating Degree Days (HDD). HDD for one day is calculated as the difference between 18°C and the average outdoor temperature for that day when the outdoor temperature is less than 18°C. For example, a day with an average temperature of 8°C has an HDD of 10. Over a month of similar days the monthly HDD would be about 300. The HDD calculation looks only at days when the average outdoor temperature is less than 18°C. Annual HDD represents the sum of daily HDD for the year.

Energy requirements for cooling are measured in units called Cooling Degree Days (CDD). CDD for one day is calculated as the difference between the average outdoor temperature for that day and 18°C when the outdoor temperature is warmer than 18°C. For example, a day with an average temperature of 21°C has a CDD of 3. A month of similar days would have a monthly CDD of about 90. The CDD calculation looks only at days when the average temperature is more than 18°C and cooling is required. Annual CDD represents the sum of daily CDD for the year.

HEATING AND COOLING TRENDS

There is a province-wide trend towards lower annual heating requirements. The annual Heating Degree Days (HDD) in the province as a whole have decreased by 600 HDD per century with the greatest reduction in energy requirements for heating in the northern parts of BC. In the Taiga Plains ecoprovince, the annual HDD have decreased by 670 HDD per century from 1900 to 2013. The Boreal Plains and Sub-Boreal Interior ecoprovinces experienced a decrease in HDD of 630 to 640 HDD per century. In the Georgia Depression ecoprovince the heating energy requirements have decreased by 310 HDD per century.

Cooling energy requirements have increased modestly throughout the province by an average of 13 Cooling Degree Days (CDD) per century. The greatest increase in energy required for cooling has occurred in the southern part of the province. The Southern Interior ecoprovince has experienced the greatest increase in annual CDD, at a rate of 25 CDD per century. The two ecoprovinces that experience the second highest rates of increasing cooling energy requirements are the Georgia Depression



Change in Annual Cooling Requirements, 1900-2013, (CDD per century)

SOURCE: Data from Ministry of Environment Climate Related Monitoring Program and Environment Canada. Trend Analysis for 1900 through 2013 conducted by PCIC, 2014 for the Ministry of Environment Climate Action Secretariat. NOTES: A positive sign indicates an increase in cooling requirements.

and the Southern Interior Mountains. Both of these regions have experienced an increase in annual cooling requirements at a rate of 21 CDD per century. The Northern Boreal Mountains have experienced an increase in cooling energy requirements at 11 CDD per century. The Taiga plains are experiencing an average annual CDD increase at 15 CDD per century.

WHY IS IT IMPORTANT?

Building managers, owners, and residents often begin interior heating when the outdoor temperature is below 18°C (although this threshold may be lower for homes constructed more recently). As outdoor temperature goes down, the amount of energy required for heating goes up.

The energy supply industry uses annual HDD figures extensively to measure and project heating requirements. Annual HDD figures help the energy industry estimate demand for residential and other heating and maximum demand on energy supply systems during extremely cold periods. All else being equal, when annual HDD decreases, there is less demand for energy for heating.

With respect to cooling, residents of warmer climates often turn on their air conditioners when the average daily outdoor air temperature, averaged over a 24-hour period, exceeds 18°C.

CDD affects energy demand because most air conditioning and refrigeration systems use electricity to operate fans and pumps. In most of BC, however, cooling places minor demands on the energy system, and CDD is not a significant factor in energy management and planning decisions. However, CDD may become more of an issue for regional energy use planning in southern BC.

WHY ARE HEATING AND COOLING REQUIREMENTS CHANGING?

During the 20th century, average annual temperatures increased across most of BC. Because heating and cooling requirements are directly linked to temperature, it is not surprising that they too should have changed during the same period.

This rise in average annual temperature is only part of the story, however. Surface warming trends and trends in daily maximum and minimum temperature vary by season and from one region of BC to another (see "Average Temperature" and "Maximum and Minimum Temperature"), affecting heating and cooling requirements.

In winter, less energy is required to keep buildings warm when average daily temperatures increase, as they have throughout BC. The trends also suggest that heating requirements have gone down mainly because winter nights are not as chilly as they were in the past (see "Maximum and Minimum Temperature").

The summer temperature trends suggest that, in the Southern Interior, Georgian Depression and Southern Interior Mountains, slightly more energy may be required to keep buildings cool during the hot part of the day because summer nights are warmer now than in the past. Buildings therefore do not cool down as much during the night (see "Maximum and Minimum Temperature").

WHAT CAN WE EXPECT IN FUTURE?

Climate models indicate that temperatures will continue to rise over BC during the 21st century and that atmospheric warming will be more pronounced in winter and summer than in spring and fall. Consequently, winter heating requirements will likely continue to decrease, and summer cooling requirements to increase.

2002 edition

HUMAN HEALTH

Warmer temperatures, and changes in precipitation and other aspects of the climate system have the potential to adversely affect human health. Although at this time there are no data that directly link climate change and health in British Columbia, studies from other regions suggest that such links may exist.

HOW CAN CLIMATE CHANGE AFFECT HUMAN HEALTH?

Climate change may increase the frequency of heat-related and respiratory illness, water contamination and water-borne diseases, vector-borne diseases, and some weather-related accidents.

Heat-related Illness: Climate models predict that over the next century summer heat waves will occur more frequently, particularly in urban areas, where buildings and pavement absorb and retain heat. Between 1951 and 1980 in Victoria, an average of three days per year were warmer than 30°C. In the 21st century, hot days are expected to more than quadruple, to 13 days per year. Hot days will be even more frequent in the Lower Mainland and the interior of BC. As a result, heat-related health impacts – including heat stroke, dehydration, and cardiovascular and respiratory illness – are expected to increase.

Respiratory Illness: Heavy emissions from motor vehicles and industrial activities can contribute to the development of smog. This is particularly a problem in Vancouver and the Fraser Valley. A component of smog – ground level ozone – is linked to respiratory irritation, affecting individuals with asthma and chronic lung disease. Even healthy individuals can experience chest pain, coughing, nausea, and lung congestion when exposed to low amounts of this ozone.

On hot days, the reactions that produce smog and ground level ozone occur more quickly. The rise in average temperature associated with climate change will likely increase the incidence of smog. The Intergovernmental Panel on Climate Change (IPCC) has therefore concluded that ongoing climate change could exacerbate respiratory disorders associated with reduced air quality in urban and rural areas.

Water Contamination: Water quality deteriorated between 1985 and 1995 at 11 percent of provincial water sampling stations. Past discharges from mining operations, non-point source pollution, and high waterfowl concentrations have made water in some communities unfit for recreation or drinking. Climate change poses additional threats. Sea level rise may inundate water systems in some low-lying coastal areas with saltwater, chemicals, and disease organisms. Extreme precipitation events may strain municipal drainage and sewage systems and increase the risk of contamination. Summer water shortages may exacerbate water quality problems in some areas by increasing the concentration of contaminants.

Water-borne Disease: Increased precipitation, runoff, and flooding associated with climate change may increase the transmission of parasites from other animals to humans through the water system. In 1995 Victoria experienced an outbreak of toxoplasmosis, a disease that causes symptoms ranging from swollen lymph glands to lung complications, lesions on major organs, and disorders of the central nervous system. The outbreak was linked to extreme precipitation, causing high levels of runoff that picked up the parasite from animal feces and carried it into drinking water reservoirs. In recent years BC has also experienced outbreaks of cryptosporidiosis, another serious water-borne disease transmitted through animal feces.

Increases in marine and freshwater temperature associated with climate change may also contribute to the survival of pathogens. Red tide, a disease of shellfish, is caused by a toxic algae that grows in warm coastal waters during the summer. Shellfish concentrate the red tide toxins in their flesh, and humans who eat contaminated shellfish can become seriously ill. Ocean warming associated with climate change may increase the incidence of red tide along the BC coast. In fresh water, warmer temperatures may create ideal conditions for the pathogen responsible for giardiasis, which is transmitted from animals to humans through water.

Vector-borne Disease: Animals, birds, and insects that carry human diseases are known as disease "vectors." Warmer temperatures associated with climate change may enable vectors – and the diseases they carry – to extend their ranges. The chance of humans contacting the disease may therefore increase. Vectors of concern in BC include rodents, ticks, and mosquitoes.

The deer mouse is the primary vector in Canada for hantavirus, and it transmits the virus to humans through its feces. When the feces dry, the virus is released into the air and can be inhaled by humans who are in the vicinity. Six cases of hantavirus in humans are known to have occurred in BC, two of them resulting in death.

Various species of ticks can carry Lyme disease and transmit it to humans. The most important vector in BC is the western black-legged tick, which is extremely common on the coast during the early spring and summer. The microorganism that causes Lyme disease has also been detected in adult ticks in the Fraser Valley.

Mosquitoes are the primary vector in North America for encephalitis. Viral transmission rates from mosquitoes can increase sharply as temperatures rise. Studies elsewhere show a correlation between temperature and the incidence of tick-borne encephalitis in humans. Swedish studies suggest that the relatively mild climate in the 1990s in Sweden contributed to increases in the density and geographic range of ticks. At high latitudes, warmer-than-usual winter temperatures were related to a northward shift in tick distribution. Further south, mild and extended autumn seasons were related to increases in tick density.

Weather-related Accidents: In general, climate change is associated with increased precipitation, flooding, landslides and extreme weather-related events. Such events may increase the incidence of accident-related injuries and deaths in BC. Other impacts of climate change – for example, reduced winter snowfall – may decrease the potential for accidents. The IPCC has concluded that in some temperate countries reduced winter deaths would outnumber increased summer deaths from climate-related factors.

WHAT CAN WE EXPECT IN FUTURE?

No cause-and-effect relationships have been established between climate change and provincial health impacts. More research is needed before we will be able to assess the degree of risk that climate change poses to the health of British Columbians. Little information is available about possible health benefits. The IPCC has also noted that potential adverse health impacts of climate change could be reduced through appropriate public health measures.

Appendix A: Climate Change Past Trends and Future Projections

Climate reflects weather conditions for a specified area over a relatively long time period, usually decades or centuries, but sometimes even millennia. It is typically described in terms of averages and extremes in such properties as air temperature, precipitation, humidity, sunshine, and storm frequency.

Climate is characterised by:

- temperatures of the surface air, water, land, and ice
- wind and ocean currents, humidity, cloudiness and cloud water content, groundwater, lakes, and water content of snow and sea ice
- pressure and density of the atmosphere and ocean, salinity and density of the ocean, composition of dry air, and boundaries and physical constants

These properties are interconnected through physical processes such as precipitation, evaporation, infrared radiation emitted by the earth and the atmosphere, vertical and horizontal movements of the atmosphere and ocean, and turbulence.

Historically, the climate of the earth has varied continuously from year to year, decade to decade, century to century, and millennium to millennium. Such changes may be the result of climate variability, climate change, or both.

CLIMATE VARIABILITY

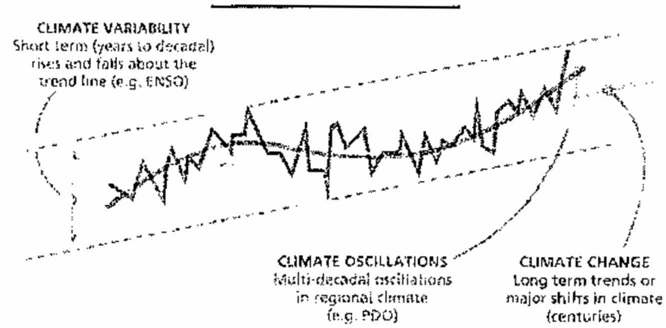
Much of the climate variability we experience involves relatively short-term changes and can occur as a result of natural alterations in some aspect of the climate system. For example, increases in the concentration of aerosols in the atmosphere as a result of volcanic eruptions can influence climate for a few years. Climate variability can also result from complex interactions between different components of the climate system: for example the ocean and the atmosphere.

The climate of British Columbia is strongly influenced by two natural patterns in the Pacific Ocean: the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

ENSO is a tropical Pacific phenomenon that influences weather around the world. El Niño, the so-called "warm phase" of ENSO, brings warmer winter temperatures and less winter precipitation to BC. La Niña, the "cool phase" of ENSO, is associated with cooler and wetter winters. During neutral years, ENSO is in neither a warm nor a cool phase and has little influence on global climate. ENSO tends to vary from the two extremes and the neutral state within two to seven years, usually staying in the same state for no longer than a year or two.

The PDO is a widespread pattern of sea surface temperature in the northern Pacific Ocean. Like ENSO, it has a warm and a cool phase. The PDO tends to remain in one phase for 20 to 30 years. It was in a cool phase from about 1900 to 1925 and from 1945 to 1977. It was in a warm phase from 1925 to 1945 and from 1977 onwards. A change from warm to cool appears to have occurred around the end of the 1990s.

Climate variability, oscillations and change



SOURCE: Adapted from original, courtesy of Pacific Climate Impacts Consortium.

The PDO is associated with cyclical changes in the sea surface temperature of the northern Pacific Ocean. Because prevailing winds blow from the North Pacific towards the BC coast and air temperature is affected by sea temperature, average air temperatures over coastal BC have also fluctuated in accordance with the phase of the PDO.

CLIMATE CHANGE

Climate change represents longer-term trends that occur over many decades or centuries.

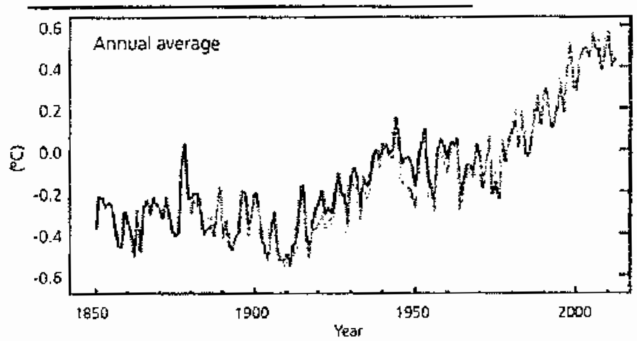
There is strong evidence that change is an ongoing feature of the global climate system. At present, however, it is occurring at an unprecedented rate. According to the AR5 report by the IPCC, global temperature, for example, has increased by 0.85°C since the 19th century. The IPCC also notes that in the last three decades, each decade has been warmer than any preceeding decade since temperature started being recorded (1850). Also, the last 30 years in the Northern Hemisphere were likely the warmest 30-year period of the last 1,400 years. Weather observations also reveal significant changes in average global precipitation and atmospheric moisture, as well as changes in patterns of atmospheric and oceanic circulation and the frequency of extreme weather.

Climate change occurs simultaneously with, and also influences, natural climate variability. For example, El Niño events may have become more frequent in recent years, and four of the ten strongest El Niño events of the 20th century have occurred since 1980.

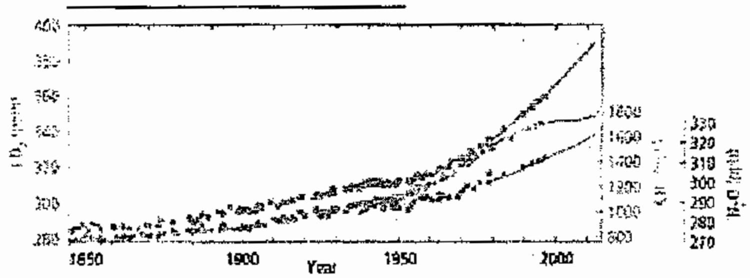
Some of the causes of climate change – including long-term changes in the amount of energy radiating from the sun and variations in the orbit of the earth around the sun – are entirely natural. Others are anthropogenic – of human origin. Some human activities – in particular the burning of fossil fuels and land-use changes – are associated with an increase in the concentration of carbon dioxide and other greenhouse gases in the atmosphere over the last century and a half. There is a strong connection between the concentration of these gases in the atmosphere and atmospheric temperature.

Anthropogenic climate change appears to be responsible for much of the atmospheric warming observed during the past century, and especially the last 60 years. The earth is currently exposed to the highest levels of CO_2 in the atmosphere in at least 800,000 years according to the IPCC's AR5 report. And some greenhouse gases, including CO_2, are persistent – they remain in the atmosphere for centuries. Climate models project that even if we stop burning fossil fuels tomorrow, the atmosphere will continue to warm for a few centuries.

Globally averaged combined land and ocean surface temperature anomaly



Globally averaged greenhouse gas concentrations



SOURCE: Adapted from IPCC, 2014, Climate Change 2014 Synthesis Report - Summary for Policy Makers, Figure SPM.1, p. 3.

OBSERVATIONS:

(left) Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005. Colours indicate different data sets.

(right) Atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2, green), methane (CH_4, orange), and nitrous oxide (N_2O, red) determined from ice core data (dots) and from direct atmospheric measurements (lines).

DISTINGUISHING PAST TRENDS

Even during a period of general global atmospheric warming, climate variability can result in cooler-than-average regional temperatures. To obtain long-term climate change trends from historical data records it is therefore necessary to identify the "signal" of climate change against the "background noise" of climate variability.

Climate variability in BC is characterized by decadal variability associated with the PDO. Short records may be too strongly influenced by this natural cycle to produce meaningful climate-change trends. Only data records that likely span one or more full cycles of the PDO, can be used to distinguish the effects of climate variability from the effects of climate change.

The majority of the climate-change and related trends described in this report were obtained through the analysis of historical data collected at weather and other monitoring stations across BC. Where trends have been identified the data show a clear "signal" of climate change.

MODELLING THE FUTURE

This report describes how the climate in BC may continue to change during the 21st century and the ongoing impacts climate change may have on marine, freshwater, and terrestrial ecosystems, and on human communities.

Most information about future projections is based on analysis by PCIC, data available on Plan2Adapt, and on AR5 reports published in 2014 by the Intergovernmental Panel on Climate Change (IPCC). The findings about future climate change are largely based on climate models – representations of the climate system that take into account relevant physical, geophysical, chemical, and biological processes. While the models have been tested to ensure that they can reasonably simulate past and current climates, they present a range of possible future climates rather than specific predictions.

Climate models incorporate scenarios of possible future states of the global climate. The most common scenarios are based on a range of socioeconomic assumptions (for example, future global population, gross domestic product) which drive the models. The IPCC Representative Concentration Pathways (RCPs) project global temperature increases ranging from 6.0°C to 8.5°C by the end of this century, accompanied by changes in precipitation and other aspects of the climate system.

In general, the ability of climate models to provide information about future changes in temperature, precipitation, and other climate variables at the regional level is improving. Mountainous regions such as BC – where valleys may have quite a different climate from adjacent mountainous terrain – present particular problems. In general, projections about temperature are more reliable than projections about precipitation or other weather elements.

Finally, information about how natural and human systems respond to shorter-term climate variability provides insights into how the same systems might respond to climate change.

ADDITIONAL RESOURCES

For more information about what climate change is, and the science behind it please refer to the Climate Insights (http://pics.uvic.ca/education/climate-insights-101) materials provided by the Pacific Institute for Climate Solutions (PICS).

For more information about future climate projections in BC and potential impacts, please see Plan2Adapt (http://www.pacificclimate.org/analysis-tools/plan2adapt), an interactive online tool provided by the Pacific Climate Impacts Consortium (PCIC).

For more information about global trends and projections please refer to the Intergovernmental Panel on Climate Change (IPCC) publications, available on their website (http://www.ipcc.ch).

Appendix B: Data and Methods
Long-Term Trends In Temperature, Derived Temperature Variables, Precipitation, and Glacier Change

DATA

Temperature, Derived Temperature Variables, and Precipitation Trends
Data was sourced from the Pacific Climate Impacts Consortium (PCIC) Data Portal (http://www.pacificclimate.org/data). The PCIC Data Portal was established by PCIC through a negotiated agreement with the Ministry of Environment's Climate Related Monitoring Program (CRMP). The result is a single portal that stores and delivers data collected by the BC Natural Resource Sector Ministries, BC Hydro and RioTinto AlCan (http://www.env.gov.bc.ca/epd/wamr/crmp.htm). The data set also includes data from Environment Canada and de-activated historical networks. This project used temperature and precipitation measurements from the station observational dataset.

This analysis requires stations with relatively long records. The early part of the analysis (early 1900's) are based on a sparse network of stations, so any understanding of the detailed climate at that time is less certain than for more recent years when there are more stations distributed broadly across the province. This issue is most critical for precipitation because its distribution across the landscape is highly complex and anomalies compared against climate normals have more detailed spatial structure than temperature does. This is especially true considering the diversity of topography in BC. This analysis reports trends for the full period for precipitation, while acknowledging that the statistical uncertainty in the trends may not fully capture the uncertainty that arises from changes in the observational network over time. However, the trends reported here are broadly consistent with other analyses carried out at a coarser spatial resolution and at individual stations.

Trends in Glacier Volume and Area Change
Glacier area change was assessed by comparing the mapped extents of glaciers from the BC Terrain Resource Information Management (TRIM) data set which are based on arial photos from the mid-1980s through the late 1990s. Glacier volume change was assessed by differencing the topography measured during the TRIM campaign from the topography measured during the shuttle radar tomography mission (SRTM) which was flown aboard the space shuttle during February 2000 (Jarvis et al., 2008).

ANALYSES

Temperature, Derived Temperature Variables, and Precipitation Trends
The general methodological approach:

1. Calculate monthly anomalies for the period of record for every station that has a climate normal associated with it. Here the climate normals were derived from the PRISM project (Anslow et al., in prep.) and are for the 1971-2000 climate normal period.
2. Compute seasonal (defined as DJF, MAM, JJA and SON) and annual anomalies for each station where monthly coverage is sufficient. This requires all three months for a seasonal anomaly and all 12 months for an annual anomaly. Anomalies are weighted appropriately based on the number of days in a given month when computing the seasonal or annual mean. For the degree day variables, number of degree days were summed on a seasonal basis for stations with sufficient data as determined through the computation of the seasonal and annual means of the temp. and precip. variables. A threshold of 5 degrees was used for growing degree days and 18 degrees was used to delineate between heating and cooling degree days.

3. For each season and complete year in all years from 1900 to 2013, interpolate the available anomalies onto a 1/2 degree grid. Then, using shape files defining the province of BC and the ecoprovinces, calculate the mean anomaly over the region of interest for each year of interest.
4. Calculate trends based on the mean anomaly for the domains of interest. Trends were calculated using the "Robust Linear Model" in R (i.e. Huber and Ronchetti, 2009). This choice was made to allow the uncertainty in the splined anomalies as well as the station density to provide weights for each year's mean anomaly. The probability of the trend being significant is provided and values greater than or equal to 0.95 may be deemed significantly different from the null hypothesis of no trend.

Trends in Glacier Volume and Area Change

The changes to glaciers that have occurred in the past several decades and which are projected to occur with climate change was intensively studied through the Western Canadian Cryospheric Network. For this report, we rely on two separate studies; the first looked at the change in volume of the glaciers in British Columbia from roughly 1985 until winter 1999-2000. The second investigated the changes in glacier area from the period 1985 through 2005. Both resultant datasets cover all glaciers in British Columbia and thus provide an excellent snapshot of both the state of glaciers in the early 2000s as well as the changes those ice masses underwent during a very warm climatological period. Glacier area change was assessed by comparing the mapped extents of glaciers from the BC Terrain Resource Information Management (TRIM) data set which are based on arial photos from the mid-1980s through the late 1990s. Glacier volume change was assessed by differencing the topography measured during the TRIM campaign from the topography measured during the shuttle radar tomography mission (SRTM) which was flown aboard the space shuttle during February 2000 (Jarvis et al., 2008). Changes in volume were computed by subtracting the earlier surface from the later surface using control points of fixed topography to assess error. The glacier analysis was done by Bolch et al. (2010) for glacier area and Schiefer et al. (2007) for glacier volume change at UNBC.

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Appendix C: Data and Methods Snow, Timing and Volume of River Flow, Sea Level, and Sea Surface Temperature

DATA

Snow Water Equivalent and Depth
Analysis of snow water equivalent and depth was done using manual snow survey data collected by the BC Ministry of Environment, provided to PCIC by the BC Ministry of Forests, Lands and Natural Resource Operations' River Forecast Centre. These data are collected in the field by taking repeat, direct measurements of snow depth and water content of the snowpack at numerous sites throughout the province. These measurements are made at monthly intervals starting January 1 and running through the latter part of the winter. These data were supplemented with April 1 snow water equivalent data from the automated snow pillow network. The automated snow pillow network operated by BC Ministry of Environment collects continuous data on snow water equivalent via its automated snow pillow network throughout BC at 71 historical locations with 51 currently operating. Data were gathered from River Forecast Centre website.

Water Survey of Canada Station ID	Water Survey of Canada Station Name
08HA001	Chemainus River near Westholme
08HA003	Koksilah River at Cowichan Station
08JB002	Stellako River at Glenannan
08JE001	Stuart River near Fort St. James
08LA001	Clearwater River near Clearwater Station
08LD001	Adams River near Squilax
08MF005	Fraser River at Hope
08MG005	Lillooet River near Pemberton
08NB005	Columbia River at Donald
08NF001	Kootenay River at Kootenay Crossing
09AE003	Swift River near Swift River

Timing and Volume of River Flow
Station information was downloaded using the Environment Canada Data Explorer – HYDAT Version 1.0 (Jan. 26, 2015). Ten stations were selected based on their association with the Reference Hydrometric Basin Network (Whitfield et al., 2012), record length, representation of major hydrologic regimes in BC and spatial location with respect to hydrologic modelling projections from the Pacific Climate Impacts Consortium at the University of Victoria (http://tools.pacificclimate.org/dataportal/hydro_stn/map/).

The Fraser River at Hope station (08MF005) was analyzed to maintain consistency with Fraser and Smith (2002) and also because it is a significant watershed in the province and provides an overview of climate-related changes to hydrology. Water extractions from the Fraser River basin through the Nechako Reservoir started in 1958. An adjusted time series was created to account for flows lost. The analyzed data are the combined 1912 to 2012 record downloaded from HYDAT and the adjusted data, which covers 1958 to 2007. This adjusted data was received from Alan Chapman in 2007 who was Lead of the River Forecast Centre at that time.

Sea Level
Relative sea level data is collected at tide gauges at numerous locations along the coast of Canada by the Canadian Hydrographic Service, part of the Department of Fisheries and Oceans. The analysis in the 2002 climate indicators report calculated trends at four long-term stations on the BC coast – Tofino, Prince Rupert, Victoria and Vancouver – and these same stations have been analyzed here. These all have data as early as 1910 but large gaps exist for some records in the 1920s and 1930s. For example, Tofino has a gap from 1920 through 1939. Prince Rupert has a similar length gap with a couple

of annual observations from 1924 and 1927. Our choice of trend estimator accommodates such gaps so infilling was not attempted. Homogenization efforts were not applied to these data owing to no indication of inhomogeneity in the data upon visual inspection of plotted annual sea level. Although sea level does change systematically with season and with interannual variability principally due to weather and ocean climatic state, seasonal trends were not computed given the interest in identifying any large scale and long-term climate driven changes.

Sea Surface Temperature

Sea surface temperature data are gathered by the Department of Fisheries and Oceans Canada as part of routine monitoring programs. The sea surface temperature data analyzed here is measured manually once daily adjacent to light stations. Water is gathered within an hour of high tide and its temperature (and salinity) are measured with well-calibrated instruments. In locations where light stations are no longer manned, the work is carried out by contractors. The program comprises 38 stations that have operated at some point since the 1930s. For this project, data were gathered from the 19 stations that have current or recent observations. Only seven had sufficiently long records to compute long-term trends.

Efforts were made to apply automated data homogenization techniques to the sea surface temperature data to correct for any potential non-climatic but systematic changes in observation values arising from, e.g., transition to contract observers or changes in instruments in time. Although the DFO has made great efforts to control the observing conditions, such issues could crop up. It was found that most of the records were resistant to such analysis likely because of the very strong decadal variability in sea surface temperature data which, makes detecting unnatural transitions very difficult. Because of this, we left the data unchanged, however, note that several stations exhibit inhomogeneities in this analysis but we are not confident enough that they are non-climatic to warrant adjusting the data.

ANALYSES

Snow Water Equivalent and Depth

The measurement taken at or near April 1 is typically viewed as a standard indicator of snow accumulation for a given year. This analysis follows this convention by examining the April 1 measurements of snow throughout the province for all years with observational data. The manual snow survey program's earliest observation year is 1935 making this a long-term dataset. The methodology and instrumentation for collecting snow depth and water equivalent has changed very little since then, producing a data set that is methodologically homogeneous. However, snow depth observation sites are subject to changing land cover conditions as vegetation changes through time, introducing some inhomogeneity. Still, the data represent a high quality 82 year-long record of snow at specific locations in the province.

The target outcome of analyzing these data is a regional quantification of changes in snow depth and water equivalent of ecoprovinces for as long a time-scale as the observational network will support. The approach consists of three steps. First, annual anomalies were computed on the station data over the 1981 to 2010 30-year normal period. Second, the anomalies were interpolated into a gridded product using thin plate spline interpolation. Finally the regional average for each year and region was taken and trends were computed from the timeseries of those averages for each ecoprovince.

Timing and Volume of River Flow

Data was processed and analyzed using code written in R. Trends were computed using the 'zyp' R Package (Bronaugh and Werner, 2015). Streamflow trends were computed for Annual Date of 1/3 of Flow, Annual Date of ½ of Flow or Centre of Timing, Annual Mean, Annual Minimum, Annual Maximum, July-August-September Minimum, April-May-June Minimum, December-January-February Mean, March-April-May Mean, June-July-August Mean and September-October-November Mean. Trends were provided in trend per unit time, trend over the period, and relative trend as per the methods of the Climate Overview

(Rodenhuis et al., 2009), which followed that of Mote et al. (2005) and trend as a percentage of the mean flow for that metric (e.g., Annual Minimum). The centre of timing (CT) is the day of the year on which one-half of the total water flow for the year has occurred (Barnett et al., 2008), where year refers to calendar year. It is important to note that we do not look at "the water year, the day between 1 October and 30 September of the next year, on which 50% of the water year streamflow has passed," which is the definition used by Hidalgo et al.(2009), who followed Maurer et al. (2007).

Trends were computed for two time periods, 1958-2012 and 1912-2012. Some stations of interest did not have records stretching back to 1912, the start date for trend analysis in the Fraser River at Hope.

Relative Sea Level
For trend analysis, the relative sea level data were converted to anomalies using the 1981-2010 average sea level for each station. Trends were analyzed using Mann-Kendall non-parametric trend analysis and slopes were calculated using the Sen slopes method. These approaches are strongly resistant to outliers in data and are better able to handle data with temporal gaps in the record.

Sea Surface Temperature
Trends in the data were analyzed on anomalies in seasonal and annual mean values relative to a 30-year climatology. To maximize the number of stations that could be included in the analysis, a 30-year normal period was chosen in which the largest number of stations contained enough data to have a climate normal calculated (requiring 75% data coverage for the given month). This resulted in a somewhat unusual climate normal period of 1968 to 1997. Because the anomalies themselves are not presented, an arbitrary normal period is acceptable. Using this approach, 15 of 19 stations had sufficient data during the climate normal period to be further considered in this analysis. Seasonal and annual climatologies were based on the monthly values and were only calculated when complete seasons or years were available thus propagating the 75% data requirement. The averages of months to make seasonal or annual climatologies were weighted by the number of days in the given month to arrive at a correct average. Trends were analyzed using Mann-Kendall non-parametric trend analysis and slopes were calculated using the Sen slopes method. These approaches are strongly resistant to outliers in data and are better able to handle data with temporal gaps in the record.

The trend analysis performed here differs from that in two published analyses of the same data over earlier periods (Cummins and Masson, 2014; Freeland, 2013).This caused the numeric trend values in those studies to differ from those presented here. Those analyses relied on linear regression to compute trend and two different approaches to adjusting uncertainty estimates to account for autocorrelation in the data. The data in Cummins and Masson (2014) were gap-filled prior to computing trends on the monthly data. Despite this, the agreement between the methods is high and the approach used for this report allows the delivery of trends as they differ between seasons.

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This is Exhibit C
referred to in the Affidavit
of Tim Lesiuk #2
sworn before me this 18th day
of December 2018

A Commissioner for taking Affidavits
within British Columbia

Government of Canada Gouvernement du Canada Canada

Natural Resources Canada

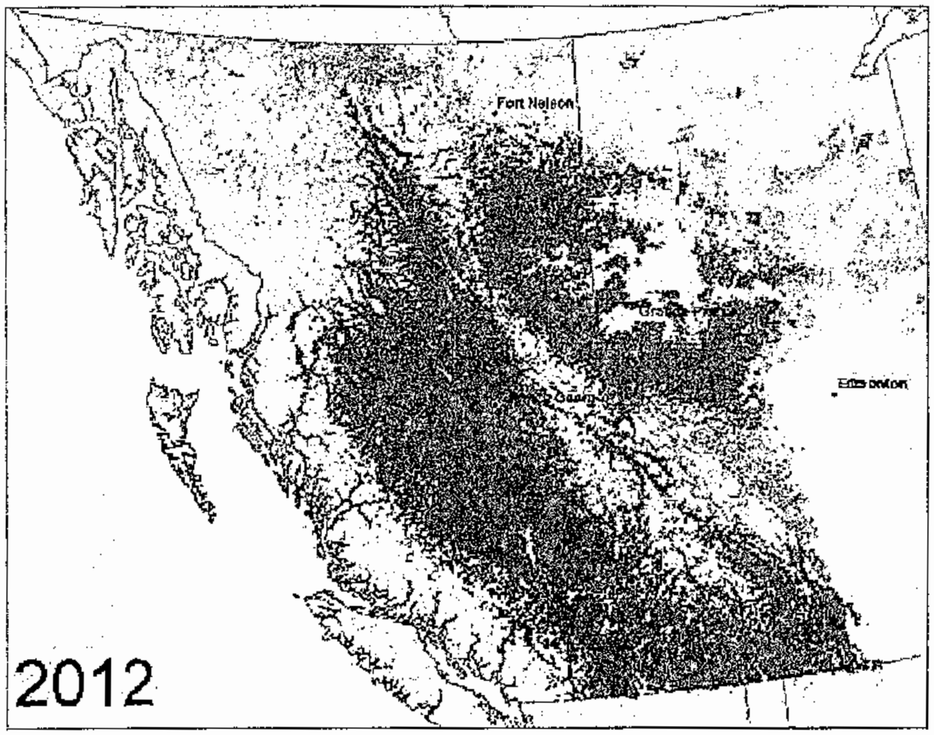
Mountain pine beetle (factsheet)

French common name: Dendroctone du pin ponderosa
Scientific name: *Dendroctonus ponderosae* Hopkins
Order: Coleoptera
Family: Curculionidae

Mountain pine beetle pupa and immature adult. Photo: D. Manastirski.

Distribution

The mountain pine beetle is native to western North America, from northern Mexico to northern British Columbia. It is also present in an isolated population of pine that is surrounded by prairie in the Cypress Hills area of southwestern Saskatchewan, which was likely infested in the early 1980s. In the 2000s, the beetle significantly expanded its range in Canada, invading new habitat east of the Rocky Mountains in northeastern British Columbia and northern Alberta.



Observed presence of mountain pine beetle from 1999 to 2012. Map data: Forest Practices Branch, Ministry of Forests and Range, Government of British Columbia; Environment and Sustainable Resource Development, Government of Alberta; Forest Insects and Disease Survey, Pacific Forestry Centre, Canadian Forest Service, Natural Resources Canada.

Hosts in Canada

Principal hosts in Canada

Lodgepole pine is the most common host in the mountain pine beetle's range in British Columbia.

Other hosts

Most species of pine that grow in the beetle's range are readily attacked, with the exception of Jeffrey pine. In Canada, these hosts include ponderosa, western white, whitebark and limber pines and, very recently, jack pine in the expanded range.

Occasional or potential hosts

Most pine species native to Canada, as well as four non-native species, have been successfully attacked when planted in the beetle's range in western North America. Non-pine hosts, such as interior spruce, Douglas-fir and western larch, are sometimes attacked during outbreaks when they grow with pine, but beetle populations do not persist long-term in non-pine hosts.

Life history

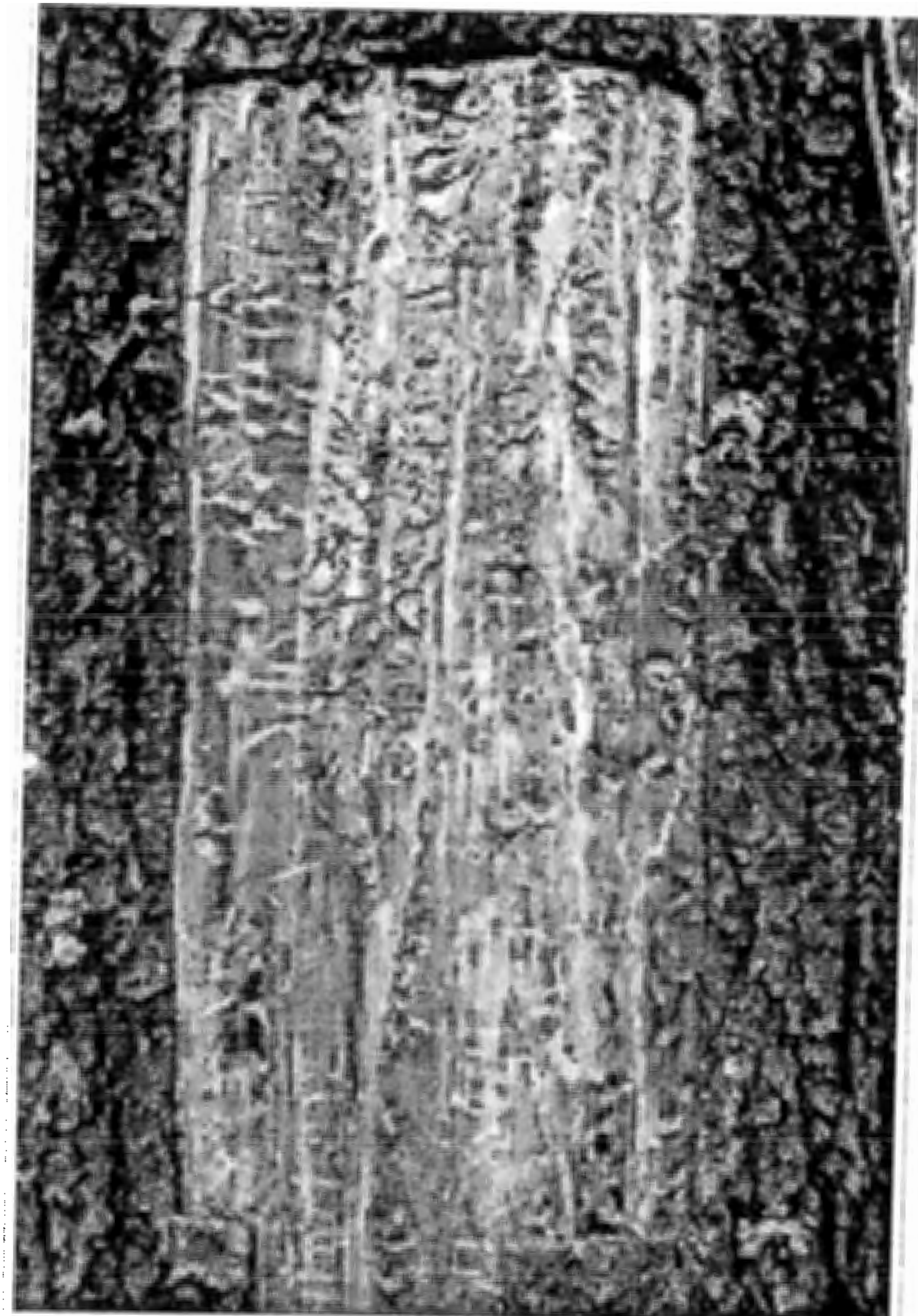
Mountain pine beetle larvae and adult. Photo: D. Manastirski.

The mountain pine beetle has a one-year life cycle in most of its range, but may take more or less time to complete its development, depending on local temperatures. Adult beetles usually disperse in July or August, depending on the region, to colonize new host trees. Females attack first and release semiochemicals called aggregation pheromones that attract more females and males to the tree. Female beetles lay eggs along the sides of vertical galleries that they excavate in the inner bark of the tree. Newly hatched larvae mine away from the egg galleries. Insects usually overwinter as larvae, completing their development the following spring and pupating in June or July.

During gallery construction, fungal symbionts carried by beetles in specialized pockets in one of the mouthparts are introduced to the trees. The fungi colonize the inner bark and sapwood, interrupting tree function and defence in addition to changing the moisture and chemistry of tree tissues in which insects are developing. The fungi sporulate in pupal chambers and new adults feed on the spores before emerging and dispersing to a new host tree.

Ecology

Trees defend themselves against mountain pine beetle attack with toxic resin. Low or endemic beetle populations cannot overcome the defences of healthy trees and attack suppressed, weak or dying trees. Suppressed and weak trees are usually poor-quality hosts for the beetles because they may already have been attacked by competing insects and the thin inner bark layer is a poor habitat.



Mountain pine beetle damage— galleries and blue-stained sapwood. Photo: K. Bleiker, CFS.

As populations increase, the mountain pine beetle is able to overwhelm the defences of larger and healthier trees through a rapid, coordinated group or mass attack. Large trees provide better habitat and produce more beetles. This results in positive feedback and rapid population growth. Tree defences may be important in regulating low or endemic populations, but they become inconsequential when beetle populations are high. Landscape-level epidemics only decline once most of the large diameter host trees have been killed or unfavourable weather causes catastrophic insect mortality.

In British Columbia, the northern limit of the beetle's range has been limited by cold winter temperatures (−40°C) and cool summers. Outbreaks have been linked to favourable weather in both summer and winter. Warm, dry summers are good for beetle development and dispersal, and drought stress reduces tree defences. Overwinter mortality is usually the largest single source of mountain pine beetle mortality; mild winter temperatures result in higher insect survival. Successive years of favourable summer and winter weather combined with an abundance of mature suitable pine hosts on the landscape have been cited as factors contributing to the massive epidemic that occurred in the 1990s and 2000s in British Columbia.

Attack and damage

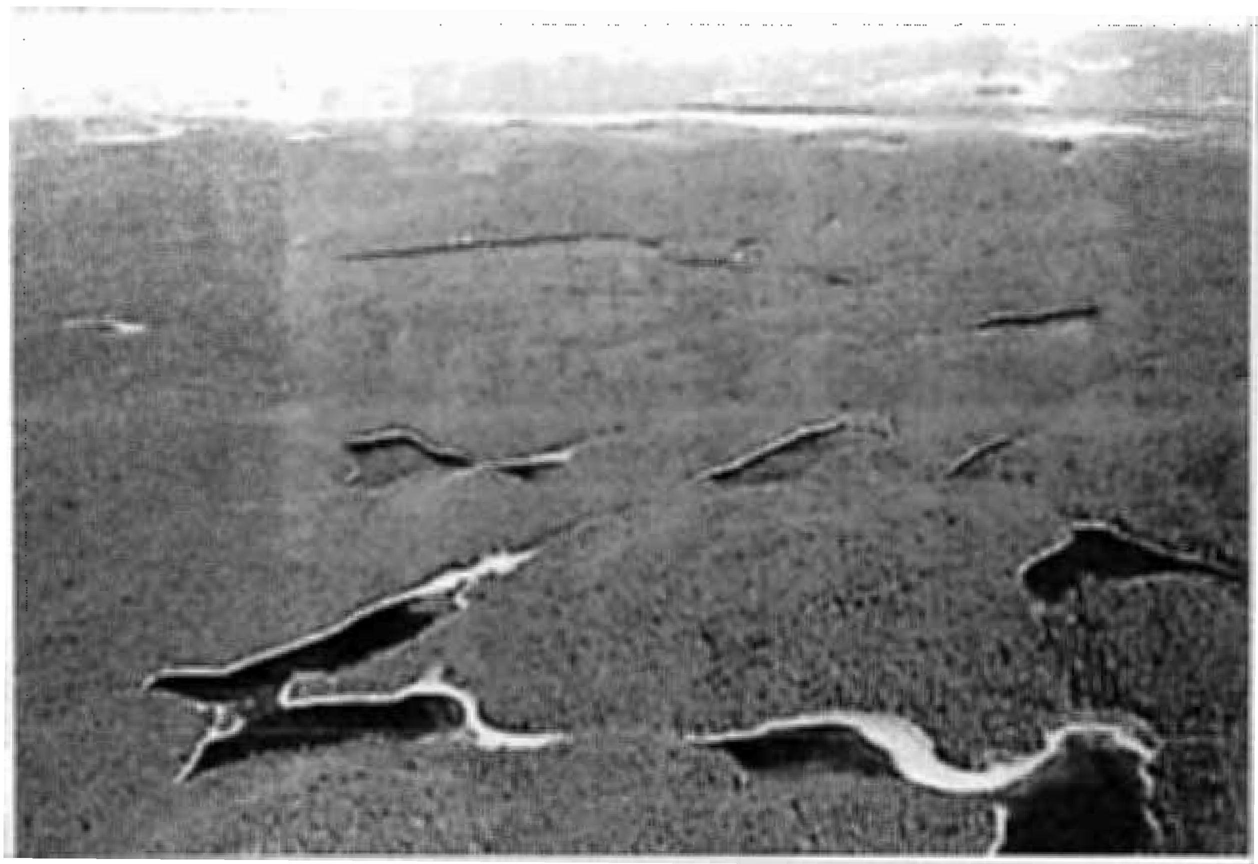
Sawdust on the outer bark around beetle entrance holes is the first sign of attack. Pitch tubes (small globs of pitch) are present on the outer bark of attacked trees within days of attack and remain visible for many years; however, pitch tubes may not be present on trees with severely compromised defences. The sapwood of successfully attacked trees appears blue in colour usually by the fall in the year of attack. Needles turn yellow, orange and then red approximately one year after attack. The crowns of some trees may start to fade in the same year as the attack, depending on environmental conditions. The red needles drop off approximately two to four years after attack and trees appear gray with no needles.

Pitch tubes on a lodgepole pine tree killed by the mountain pine beetle. Photo: K. Bleiker, CFS.

Status in Canada

The largest recorded mountain pine beetle epidemic occurred in the 1990s and 2000s in British Columbia. Over 18 million hectares of forest were impacted to some degree, resulting in a loss of approximately 723 million cubic metres (53%) of the merchantable pine volume by 2012. The epidemic peaked in 2005: total cumulative losses from the outbreak are projected to be 752 million cubic metres (58%) of the merchantable pine volume by 2017, when the epidemic will have largely subsided in British Columbia.

Several times in the 2000s, beetles from the massive epidemic in central British Columbia were carried on upper atmospheric winds across the biogeoclimatic barrier posed by the Rocky Mountains. The insects were deposited in northeastern British Columbia and northwestern Alberta. These long-distance dispersal events resulted in a significant increase in the distribution of the mountain pine beetle in Canada. The beetle is now established in lodgepole–jack pine forests in northern Alberta and threatens to spread east across Canada's boreal forest if conditions are favourable. The mountain pine beetle has also moved northwards and in 2012 was reported north of 60° latitude in the Northwest Territories for the first time, although the fate of this small population is uncertain.



Lodgepole pine trees killed by mountain pine beetle near Bonaparte Lake, BC. Photo: K. Buxton, BC Ministry of Forests, Lands and Natural Resource Operations.

Contact: Kathy Bleiker

Links

Canadian Forest Service publications on mountain pine beetle

► References

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This is Exhibit D
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of December 2018

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Attributing extreme fire risk in Western Canada to human emissions

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Abstract Canada is expected to see an increase in fire risk under future climate projections. Large fires, such as that near Fort McMurray, Alberta in 2016, can be devastating to the communities affected. Understanding the role of human emissions in the occurrence of such extreme fire events can lend insight into how these events might change in the future. An event attribution framework is used to quantify the influence of anthropogenic forcings on extreme fire risk in the current climate of a western Canada region. Fourteen metrics from the Canadian Forest Fire Danger Rating System are used to define the extreme fire seasons. For the majority of these metrics and during the current decade, the combined effect of anthropogenic and natural forcing is estimated to have made extreme fire risk events in the region 1.5 to 6 times as likely compared to a climate that would have been with natural forcings alone.

Keywords Event attribution · Fire weather · Extremes

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1 Introduction

A wildfire near Fort McMurray, Alberta, Canada in early May 2016 burned almost 600,000 ha, but was most notable for displacing over 80,000 people (Government of Alberta 2016) and causing $3.5 billion in insured losses (IBC 2016). Following such an extreme event, questions arise regarding the extent to which human-induced climate change contributed to the event.

Wildfires in Canada burn approximately 2.1 million ha annually (Natural Resources Canada (NRCan) 2016). While large fires, classified as those burning more than 200 ha, constitute only 3% of all fires in Canada, they are responsible for about 97% of the area burned (Stocks et al. 2003). The occurrence and behavior of a fire is dependent on an ignition source, available fuels to burn, and weather conditions favorable for spread (Parisien et al. 2011), and can also be influenced by human suppression efforts. Williams and Abatzoglou (2016) review fire-modeling studies that assess climate influences on wildfire activity.

The Canadian Forest Fire Danger Rating System (CFFDRS; Stocks et al. 1989) is widely used to assess and predict wildfire risk and behavior across northern North America and is also applied in many other regions around the globe. CFFDRS is composed of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987), which uses weather conditions to calculate fire potential, and the Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), which uses information from the FWI and evaluates the behavior of an ignited fire for different fuel types.

As wildfires have numerous impacts, many studies have investigated changes to fire risk under future climate projections (Flannigan et al. 2009). Through lengthening of the fire season (Flannigan et al. 2013; Liu et al. 2013), increased days with spread potential (Wang et al. 2015), increased fire risk (de Groot et al. 2013), or projected increases in the number of fires (Wotton et al. 2010; Krawchuk et al. 2009) and area burned (Balshi et al. 2009; Flannigan et al. 2005), a heightened fire risk is expected in Canada and the USA under scenarios with increasing anthropogenic greenhouse gases. Jolly et al. (2015) used reanalyses to demonstrate an increase in fire season length has already been seen globally through 2013. Flannigan et al. (2016) estimated up to a 15% increase in precipitation is needed to offset each degree of warming in terms of the FWI indices and thus increasing temperatures will result in more days with high fire potential. Increased fire risk has the potential to exceed the capabilities of current fire management agencies (Podur and Wotton 2011; Flannigan et al. 2009).

To assess the anthropogenic influence on fire risk in western Canada, we utilize an event attribution framework (NASEM 2016), which aims to quantify the influence of anthropogenic forcings on the frequency (our focus in this paper) or magnitude of specific classes of extreme events. The methodology generally involves comparing the probability of a particular event's occurrence in a world with observed emissions (ALL forcing = natural (NAT) + anthropogenic (ANT)) and in a counterfactual world (NAT only). Because direct observations of the counterfactual world are unavailable, event attribution studies typically rely on large ensembles of climate model simulations. Only a few studies have pursued the attribution of fires and wildfire risk directly, though attribution of increased temperatures and drought events can also lend insight into fire risk. Using the strong relationship between temperature and area burned, Gillett et al. (2004) detected an anthropogenic contribution to increasing area-burned trends in Canada. With a large ensemble from CESM1, Yoon et al. (2015) found a deviation in drought and fire risk between simulations that included anthropogenic forcings and those with only natural variability beginning in the 1990s and thus attributed an increased fire risk in California to human emissions. Abatzoglou and Williams (2016) found that anthropogenic signals account for approximately half of the increasing trends in fuel aridity and fire season length in the western USA. Finally, Partain et al. (2016) demonstrated that the fuel conditions leading to the severe 2015 fire season in Alaska were more likely with ALL forcings than in a counterfactual world.

The goal of this paper is to use an event attribution perspective to quantify the influence of anthropogenic forcings on extreme wildfire risk in a region of western Canada that includes Fort McMurray. Fourteen metrics are utilized to define extreme fire risk on a fire-season basis for the 2011–2020 climate and the probabilities of these extreme fire seasons are compared between a scenario with ALL forcings and a counter-factual scenario with only NAT forcings. In Section 2, we introduce the observations, model, and region used in this analysis. Section 3 provides an overview of CFFDRS and the calculation of its indices. The event attribution methodology, event definitions, and results are presented in Section 4, with conclusions in Section 5.

2 Data

2.1 Observations and region

The Global Fire Weather Database (GFWED; Field et al. 2015) is a gridded dataset of daily FWI indices. The data are available on the 1/2° by 2/3° grid of the MERRA reanalysis (Rienecker et al. 2011), beginning in 1980. GFWED provides the four main FWI System indices as well as the daily input weather data for the FWI-system standard of local noon values. The temperature, relative humidity (RH), and wind speed inputs for the FWI indices calculated here are from GFWED. Precipitation is obtained from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset (Beck et al. 2016), which combines surface-based and remotely-sensed observations and reanalysis products to create a global 3-hourly precipitation dataset on a 0.25° grid. The data were aggregated to 24-h accumulations as close to the GFWED data as possible and interpolated to the MERRA grid. See the supplementary material for more discussion of the choice of precipitation dataset. The observations are mainly used for bias-correcting the model data.

We use the homogeneous fire regime (HFR) zones defined by Boulanger et al. (2012), who used a cluster analysis of fire characteristics and climatologies to refine the eco-classifications of the Ecological Stratification Working Group (ESWG) (1996) to regions more suited to wildfire analyses. The HFR zones in western Canada were numbered by the authors and the region containing Fort McMurray was selected (Fig. 1). This region, covering approximately 5.7×10^7 ha or 267 GFWED grid boxes, will be referred to as HFR9 herein.

2.2 Model

The model simulations are from large ensembles of the Canadian Earth System Model version 2 (CanESM2; Arora et al. 2011; Fyfe et al. 2017). The first large ensemble contains 50 ensemble members (also referred to as realizations) with ALL forcing and the second contains 50 ensemble members with NAT forcing. NAT forcing includes solar and volcanic influences, while ALL forcing is a combination of natural forcing and the anthropogenic components (greenhouse gases, aerosols, land use, etc). The NAT simulations are available through 2020 and ALL simulations through 2100, with years beyond 2005 forced with RCP8.5. Herein, ALL data are not used beyond 2020 and there is a negligible difference between RCPs for this period (van Vuuren et al. 2011). Daily values of maximum temperature, mean wind speed, and

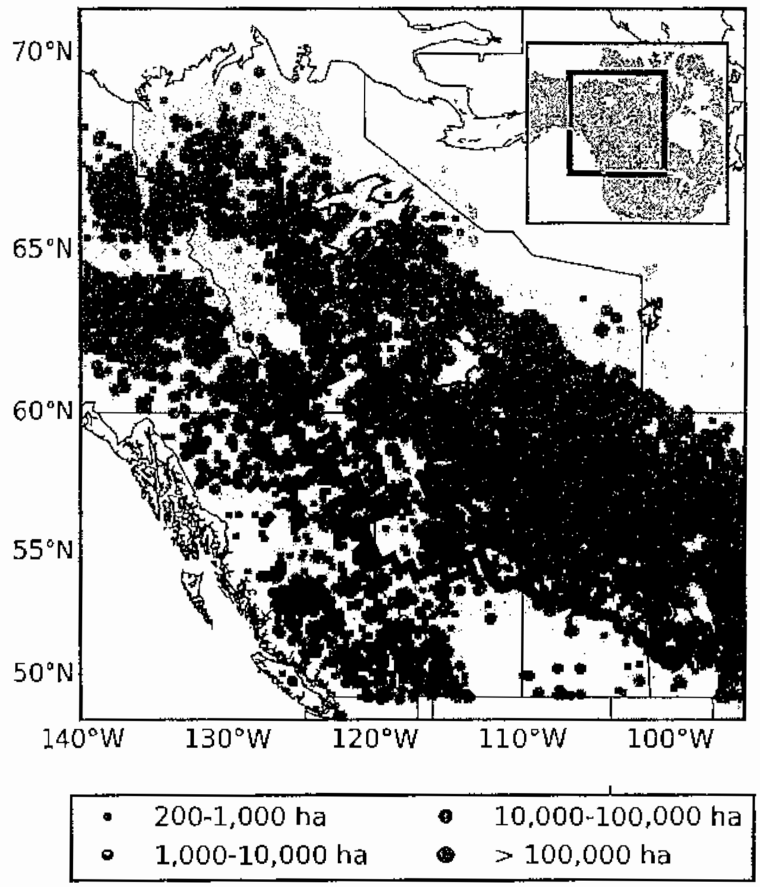

Fig. 1 Western Canada region used in this study. The *green* shading represents the Boreal zone (Brandt 2009). *Red* points are ignition locations of large fires (>200 ha) for the 1980–2014 period from the CNFDB, scaled by fire size. *Black* region is HFR9 and the *blue* dot is Fort McMurray

total precipitation were acquired from the model output; RH was calculated using the model-supplied specific humidity. More details on the CanESM2 ensemble can be found in the supplementary material.

The topography of the region, namely the Western Cordillera, can have an impact on the local weather and thus on the fire indices and these effects may not be captured adequately with the coarse resolution (2.81°) of CanESM2. Other studies have employed simple downscaling models (Flannigan et al. 2013; Wang et al. 2015) to increase resolution or statistical models to relate model outputs to the number or area of fires (Wotton et al. 2010; Balshi et al. 2009). Here, the large ensemble output was downscaled to the resolution of the GFWED data and then bias corrected following the methodology of Cannon (2017), which bias corrects the marginal distributions and maintains the multivariate dependence structure between the four variables (tair, RH, wspd, prcp). If debiased separately, the relationship between weather variables could be altered, which would have implications for the calculation of the CFFDRS indices (Cannon 2017). The downscaling/bias correction considers internal variability between realizations and maintains the separation between the ALL and NAT responses; the procedure is described in more detail in the supplementary material.

3 CFFDRS

3.1 Indices

The FWI System (Van Wagner 1987; see Table 1) uses weather variables to assess the risk of fire ignition and spread. The system includes three indices (FFMC, DMC, and DC) that describe the moisture available in fuels of increasing depths and the FWI index, which provides a summary measure of the fire potential. For all indices, larger values indicate higher fire risk. The FWI system indices are calculated daily using observations at local noon and depend on the previous day's index. We use the recommended values (NRCan 2016) to initiate the calculations on the first day of the fire season and ignore overwintering adjustments. Indices from the observations and downscaled model simulations were calculated by grid box using the same routine. More detail regarding the interpretation of the indices and their use by fire managers is available in Wotton (2009).

The FBP System incorporates some of the FWI indices to provide more detail on the expected behavior of an ignited fire, with the calculations (Forestry Canada Fire Danger Group 1992) dependent on specific fuel types (Nadeau et al. 2005). The three main fuel types for HFR9 are Boreal spruce (C2), Lodgepole pine (C3), and leafless aspen (D1) (S. Taylor, personal communication). We focus on C2 due to its prevalence in northern Alberta (Nadeau et al. 2005), but include results for C3 and D1 in the supplementary material.

An example of the relationship between the FWI and fires in HFR9 is shown in Fig. 2, which compares density curves of the FWI values for all days and all gridboxes with FWI values for days and gridboxes corresponding to large fires. Fire data were acquired from the Canadian National Fire Database (CNFDB; Stocks et al. 2003). The maximum FWI in the first four days following ignition is assigned to each fire; this window was chosen based on when a fire consumes most of its fuel (Amiro et al. 2004). In general, large fires occur on days with greater fire potential (larger FWI). There are many days every year that experienced extreme fire risk but either lacked an ignition source or any ignited fires were suppressed quickly. Additional analyses of the relationship between large fires and the FWI and FBP indices can be found in Amiro et al. (2004); Kiil et al. (1977).

3.2 Fire season

There is no standard definition for the fire season. The official NRCan recommendation (Turner and Lawson 1978) is to begin the calculation of the FWI System indices after three consecutive days without snow cover in regions that experience significant winter snow cover, or after three consecutive days with noon temperatures over 12 °C. All of the grid boxes in HFR9 see significant winter snow cover.

For observations, following the GFWED (Field et al. 2015), a grid box is snow covered if snow depth is greater than 1 cm. The fire season start dates were calculated after three consecutive days without snow cover, beginning 01 March. The grid boxes in HFR9 generally start their fire seasons in late April or early May (Fig. S1a), whereas regions farther north or at higher elevations start later in the year. The fire season ends with the first snowfall, defined as the first day after 01 July with snow cover, which occurs in September for

Table 1 List of fire weather and behavior indices from the CFFDRS and the input variables they depend on, including air temperature (tair), relative humidity (relh), and wind speed (wspd) at local noon and 24-h precipitation (prcp)

System	Index		Description	Extreme	Input variables
FWI	Fine Fuels Moisture Code	FFMC	moisture in surface fuels; memory: 3 days; prcp threshold: 0.5 mm	91	$tair^{+}$, $relh^{-}$, $prcp^{-}$ $wspd^{+}$
FWI	Duff Moisture Code	DMC	moisture in decaying litter, upper layers; memory: 14 days; prcp threshold: 1.5 mm	60	$tair^{+}$, $relh^{-}$, $prcp^{-}$
FWI	Drought Code	DC	moisture in deep layers, large debris; memory: 51 days; prcp threshold: 2.8 mm	425	$tair^{+}$, $prcp^{-}$
FWI	Initial Spread Index	ISI	potential fire spread rate	15	FFMC, $wspd^{+}$
FWI	Buildup Index	BUI	potential fuel available	90	DMC, DC
FWI	Fire Weather Index	FWI	summary of fire potential	30	BUI, ISI
FWI	Daily Severity Rating	DSR	rescaled FWI for categorical interpretation	15	FWI
FBP	Surface Fuel Consumption	SFC	amount of fuel consumed by the fire (kg m^{-2})	4	FFMC, BUI, fuel type
FBP	Rate of Spread	ROS	rate (m min^{-1}) at which the fire head (leading edge) moves	18	ISI, BUI, fuel type
FBP	Head Fire Intensity	HFI	intensity (kW m^{-1}) at the fire head	10,000	ROS, SFC

Superscripts indicate whether increasing values of the input weather variables result in increased (+) or decreased (−) values of the index. Descriptions from (Wotton 2009), memory from (Field et al. 2015), extreme values from (NRCan 2016)

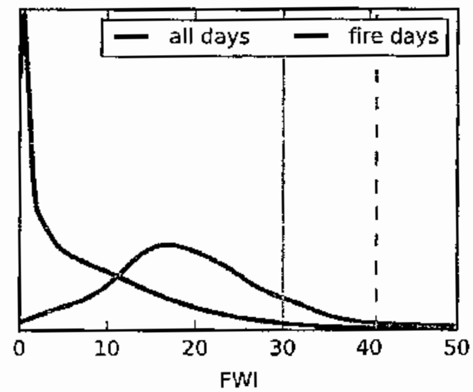

Fig. 2 Density curves for all Fire Weather Index (FWI) values during the fire season (MJJAS) by grid box in HFR9 using the GFWED-MSWEP data for 1980–2014 (*black*) and for only grid boxes where a large fire ignited, using the maximum FWI value in the first four days (*red*). *Vertical bars* indicate extreme values of the index defined by NRCan (*solid*) and the value at the time of ignition of the Fort McMurray fire (*dashed*). About 800 values went into the *red curve* and on the order of 10^6 values are summarized by the *black curve*

much of the region (Fig S1b). The resulting fire season length averages approximately 150 days (Fig. S1c) in HFR9.

For CanESM2 simulations, a simple statistical model was derived to predict the fire season start date for each year based on mid-spring growing degree days; more information regarding its calibration can be found in the supplementary material. The fire season end date was defined as the first day after 01 July where a grid box reported precipitation over 0 mm and a noon temperature below 5 °C.

4 Event attribution

4.1 Setting up the event attribution

A detection and attribution analysis (Bindoff et al. 2013) was used to assess whether anthropogenic influence has had a discernible effect on the base climate state in the larger western Canada region. Evidence that anthropogenic influence has altered the base state would increase confidence in the attribution of extreme events, which can be viewed as departures from this altered base state (NASEM 2016). Mean temperatnre was chosen due to its robust detection globally (Bindoff et al. 2013) and throughout many regions (Stott 2003; Zhang et al. 2006), its observational coverage, and its well understood relationship to increased greenhouse gases. As there can be smaller signal-to-noise ratios at the regional level and among other variables, it can be more difficult to provide a robust attribution (Stott et al. 2010). Performing a detection and attribution analysis for temperature over a larger region and longer time period helps to reduce the impact of noise on such analyses.

Observed monthly temperatures over land areas from the CRU-TS3 dataset (Harris et al. 2014) on a 0.5° grid were averaged over western Canada (Fig. 1). Similarly, monthly average temperatures from CanESM2 ALL and NAT realizations were averaged over the land grid boxes for this region. A detection and attribution analysis was performed for the longest period available (1960–2014); a thorough description of the methods applied here can be found in Kirchmeier-Young et al. (2016).

The ALL forcing signal was detected in the observations (Fig. S2) for the fire season (MJJAS), though CanESM2 overestimates the warming during this period. After scaling the model response to be consistent with the observations, the result is an attributed warming trend of about 1 °C over the period for which the FWI indices can be calculated (1980-2014). As anthropogenic forcing has had a demonstrable influence on the region, it is reasonable to pursue an event attribution analysis for a more localized region and for other variables that, while influenced by temperature change, likely present smaller signal-to-noise ratios.

4.2 Event definitions

A key first step for event attribution is framing the attribution question (NASEM 2016), which includes determining the spatial and temporal characteristics and climate variable to define the event of interest. Although the events chosen for attribution analyses are typically inspired by societally-relevant extreme events, selection bias becomes a concern when using an event definition that is too specific (e.g., observed extreme at a point location). Furthermore, using multiple event definitions can increase the robustness of event attribution results (NASEM 2016).

We use the class type of event definition (NASEM 2016) by defining an event as all possible outcomes for which a particular metric exceeds a chosen threshold (Table 2). First, we define a class of events for each FWI index by requiring the 90th percentile of daily index values for each fire season to exceed an NRCan (2016) defined "extreme" threshold.

Table 2 Event attribution results for many extreme fire risk metrics

Event	p_0	p_1	PN	PS	RR
Fire Season 90th percentile					
FWI > 30	<0.01	0.03	0.83	0.03	5.97
FFMC > 91	0.05	0.15	0.66	0.11	2.95
DMC > 60	0.23	0.36	0.35	0.17	1.55
DC > 425	0.39	0.56	0.31	0.29	1.45
ISI > 15	<0.01	<0.01	-	-	-
BUI > 90	0.15	0.26	0.44	0.14	1.78
Significant spread potential					
> 38 days	0.03	0.12	0.74	0.09	3.90
> 25%	0.04	0.11	0.65	0.08	2.82
ROS p90 > 18 [C2]	<0.01	<0.01	1.00	<0.01	10^9
Fire Intensity Classes					
> 38 days Class 5/6 [C2]	0.16	0.37	0.55	0.24	2.22
> 76 days Class 5/6 [C2]	<0.01	<0.01	0.96	<0.01	22.52
HFI p90 > 10,000 [C2]	0.08	0.23	0.63	0.16	2.72
Fire Season					
Fire season starts by 15 Apr	0.09	0.19	0.52	0.11	2.10
Fire season ends after 31 Sep	0.09	0.25	0.65	0.18	2.86
Fire season > 165 days	0.05	0.20	0.76	0.16	4.12

Values are rounded to two decimal places for display purposes. See Table S1 for uncertainties. Attribution metrics are not calculated for ISI as the extreme threshold exceeds any regional values realized in either the ALL or NAT simulations

FWI index percentiles have been used in other studies (Wotton et al. 2010; Parisien et al. 2011; Wang et al. 2015) and are a better indicator of extreme fire days than a measure of central tendency. The NRCan thresholds are defined for all of Canada and may not completely characterize local extremes. For reference, the maximum value of each index during the first 4 days of the Fort McMurray fire, based on data from the Fort McMurray airport weather station, was FFMC-95, DMC-56, DC-370, ISI-21, BUI-81, FWI-40 (M. Flannigan, personal communication). Bearing in mind the inherent difference between station and gridded observations, these values correspond, respectively, to the >99, 94, 89, >99, 95, >99th percentiles in the corresponding grid box of GFWED data.

We also considered events defined in terms of days with significant spread potential, by using the 90th percentile value of the ROS (Rate of Spread) and also the definition of Wang et al. (2014) that determines spread days in a rain-free period as those with FWI (Fire Weather Index) ≥19 and DMC (Drought Moisture Code) ≥20. Spread days are expressed as the number of days per season or the percentage of the fire season length, with thresholds for an extreme season being 38 days (25% of the climatological mean season length) or 25%, respectively. We also use the fire season 90th percentile of Head Fire Intensity (HFI) and metrics characterized by the number of days in fire intensity classes 5 and 6 (HFI > 4,000; NRCan 2016). Finally, we look at metrics describing the fire season, including start and end dates and the length of the season.

4.3 Methodology and metrics

For each of the metrics discussed above, the probabilities of an event occurring under ALL and under NAT forcing were calculated by pooling the values from all realizations for a chosen decade. Each metric was calculated by grid box and then averaged across HFR9. An example using the 90th percentile of the FWI is shown in Fig. 3. For each realization, each year and each grid box, the 90th percentile of daily FWI values is determined and averaged

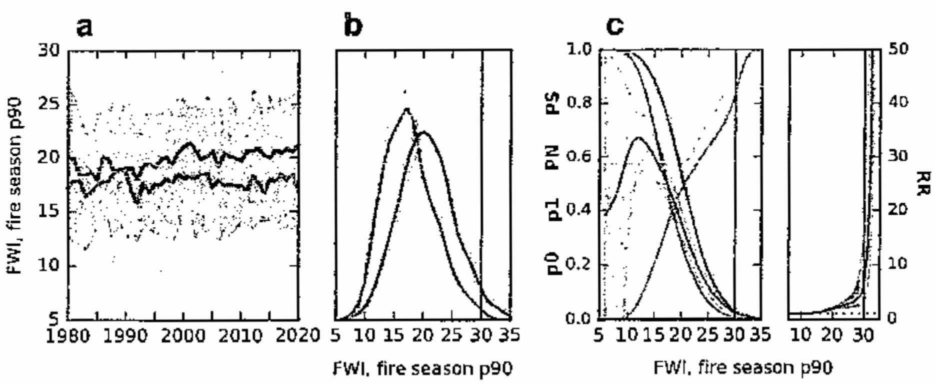

Fig. 3 **a** Time series of fire season 90th percentile values of the Fire Weather Index (FWI) for the ALL forcing ensemble mean in *blue* and NAT forcing ensemble mean in *green*. Shading represents the 5th–95th percentile range across the ensemble. **b** Density plots for 2011–2020 for ALL in *blue* and NAT in *green*, pooling values from the ensemble members and using a Gaussian kernel density estimator. A non-parametric 90% uncertainty range is *shaded*, determined through bootstrapping. The *vertical bar* represents the threshold for an extreme value; for comparison, the Fort McMurray station saw an FWI value of 40 on the day of fire ignition. **c** Plots of p0, p1, PN, PS, and RR for a fire season 90th percentile value more extreme than the threshold on the horizontal axis. The probabilities (p0 and p1) are determined by empirically integrating the density curves and the shaded uncertainty ranges are a result of the uncertainty on the density curves

over HFR9; the result is a value for every year and every realization. Time series of the 90th percentile of FWI (Fig. 3a) show that as time progresses, the separation of the ALL (blue) and NAT (green) ensemble means increases, with a slight increasing trend under ALL forcing and no trend under NAT forcing.

Choosing the current decade, 2011–2020, the values from each year and each realization are pooled together (500 years total) and density curves estimated (Fig. 3b). The density curve for ALL (blue) is shifted toward slightly larger values of FWI than the NAT curve. These densities are then used to calculate the probability of a particular event; p_0 is the probability under NAT forcing and p_1 the probability of the same event under ALL forcing (Fig. 3c). Numerous thresholds to define events (horizontal axis) are used. Both p_0 and p_1 decrease with increasing severity of FWI values, but p_1 decreases more slowly as the extreme events are more likely with ALL forcing.

The probabilities are used to calculate three event attribution metrics:

$$PN = FAR = 1 - \frac{p_0}{p_1} \tag{1}$$

$$PS = 1 - \frac{1 - p_1}{1 - p_0} \tag{2}$$

$$RR = \frac{p_1}{p_0} \tag{3}$$

The probability of necessary causality (PN) and the probability of sufficient causality (PS) were introduced in Hannart et al. (2016). PN describes the probability that ALL forcing is a necessary cause of the particular event; that is, that ALL forcing is required for the event's occurrence. PS describes the probability that ALL forcing is sufficient for the event, such that a scenario with ALL forcing will see the occurrence of this event every time. Any negative values of PN or PS are set to 0. PN is also the fraction of attributable risk (FAR; Stott et al. 2004), which describes the fraction of the risk of an event's occurrence contributed by the anthropogenic (ANT) component. Finally, the risk ratio (RR) describes how many times as likely the event occurrence is with ALL than with NAT.

The resulting curves for the event attribution metrics are shown in Fig. 3c. PN increases with increasing severity of FWI values. A PN value of approximately 0.8 for a fire season 90th percentile value of the FWI exceeding 30 means that 80% of the risk of this event is due to anthropogenic (ANT) forcing, there is an 80% chance that ANT forcing is required for this event to occur, or eight out of ten occurrences of this event would not have happened with only NAT forcing. The PS values are small for the more extreme FWI thresholds, as such events are rare with both forcing scenarios (see Fig. 3b). Finally, the RR is greater than 1 (the event is more likely under ALL forcing) for all FWI thresholds. RR values increase rapidly for the more extreme values of FWI. An RR of 10 would imply the occurrence of that event is 10 times as likely under ALL forcing than under NAT forcing.

4.4 Results

All of the metrics show density curves for ALL forcing that favor more extreme values compared to NAT forcing for 2011–2020 (Fig. S3). For the FWI indices, this is likely due to the strong signal seen in temperature and to a lesser extent the difference in wind speed between the two forcing scenarios (Fig. S4, S5). The extreme thresholds (vertical bars) are rare events for many of the indices, resulting in small values of p_1 and even smaller values of p_0 for these events (Table 2). For the FWI indices, the RR values range from about 1.5

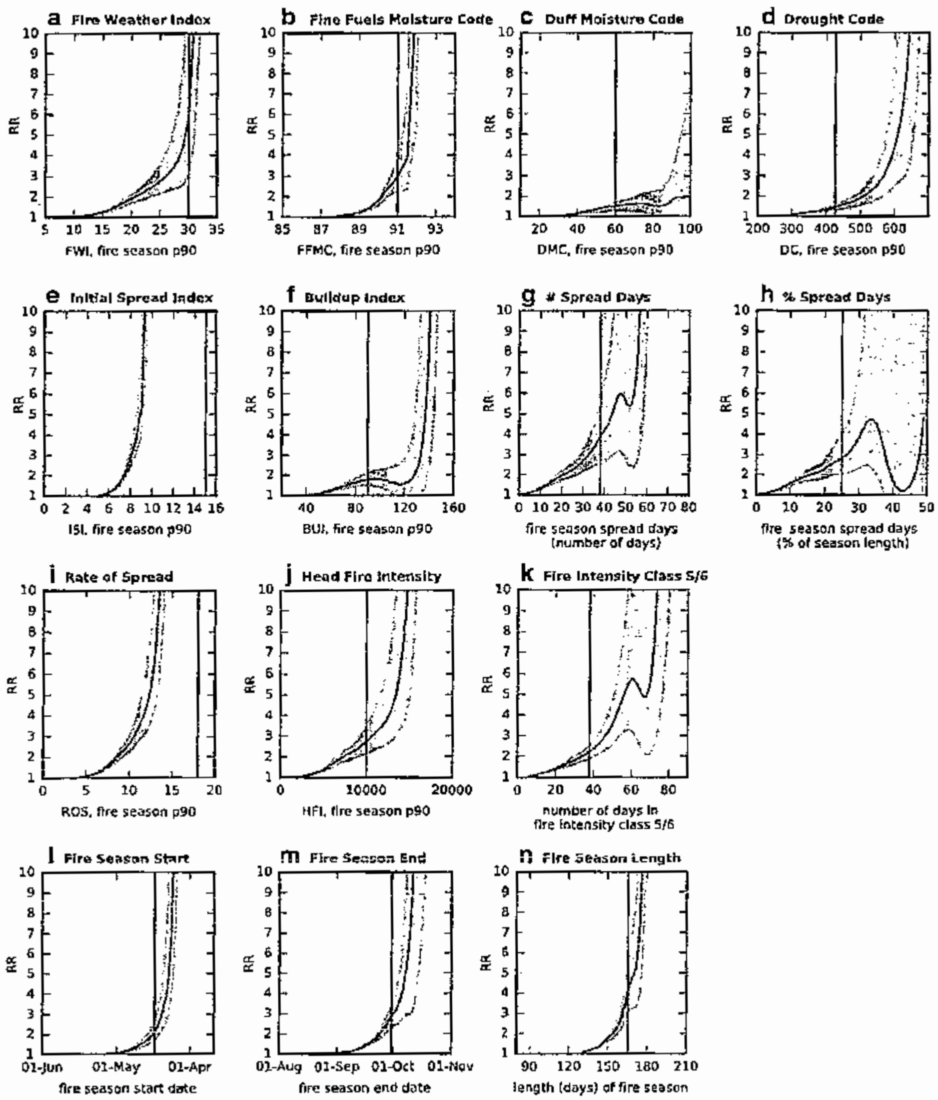

Fig. 4 The risk ratio (RR) for many metrics based on a 2011–2020 climate. Values are for an event more extreme than that indicated on the *horizontal axis* and the *vertical bar* represents the threshold for an extreme value (see Table 2 and Table S1). The uncertainty range for each RR curve is *shaded* and was calculated using a bootstrapping method. The FBP metrics in panels (i)–(k) use the C2 fuel class

to 6 times as likely under ALL forcing and the confidence intervals on these values are generally small (Fig. 4).

The significant spread days show similar results between the counts and percentage metrics, with approximately 70% of the event risk due to anthropogenic forcings (Table 2). Under ALL forcing, it is almost three times as likely for a fire season to have significant spread potential on more than a qnarter of its days. Using the 90th percentile value of the ROS (Rate of Spread) sees smaller probabilities for events exceeding the extreme threshold and much stronger attribution results, with a PN value indicating ANT forcing is a necessary cause.

Events for the 90th percentile of the HFI (Head Fire Intensity) and the number of days in the top fire intensity classes are several times as likely under ALL forcing (Table 2). These results are sensitive to fuel type (Fig. S7) though it is expected that a spruce forest (C2) will have more burn potential than one with leafless aspen (D1).

An increased fire season length under ALL forcing (Fig. S3m) is consistent with other studies that demonstrated extended fire seasons under future scenarios including increased anthropogenic emissions (Flannigan et al. 2013; Liu et al. 2013). There is a 76% chance that ANT forcing is necessary for a fire season exceeding 165 days and such an event is 4 times as likely than with NAT forcing alone (Table 2). This is influenced by both a later end date and earlier start date to the fire season.

Generalizing to other thresholds, RR (Fig. 4) and PN (Fig. S8) curves are shown for an event more extreme than the given index value. Consistent with the densities (Fig. S3), all metrics see increasing PN values for more extreme thresholds, indicating an increased contribution of ANT forcing to the occurrence of such events. This is consistent with increasing RR values for more extreme thresholds. PN reaches 1.0 in the upper tail of the ALL distribution for most metrics with very large RR values, which would implicate ANT forcing as a necessary cause. Although the exact RR values can be sensitive to the estimation of very small probabilities, such events would be considerably more likely to occur with ALL forcing than with NAT forcing.

5 Discussion and conclusions

This study uses a single model ensemble; although the large number of realizations should adequately represent internal variability, detection and attribution analyses can benefit from multi-model ensembles (Hegerl and Zwiers 2011) that reduce the influence of a particular model's biases. The simulations used here were debiased relative to a reanalysis product, which requires assumptions about its representativeness for the region. The downscaling and bias correction routines may also introduce their own sources of error. Additionally, the bias correction does not fully correct the trends and the model used here may overemphasize the warming trend for this region, which would result in over-confident attribution. Limited coverage of observations in this region presents challenges for evaluating reanalysis or model performance.

Using several event definitions strengthens an event attribution result (NASEM 2016) and those chosen here include numerous ways to represent extreme fire risk and potential. These event definitions were chosen with the consultation of a fire scientist (S. Taylor, personal communication) and represent extreme fire risk from a climate perspective; at a local level, fire managers may require different metrics and thresholds to best define fire risk (Wotton 2009). Furthermore, this analysis does not consider changes to forest health or composition as a result of climate change (Gauthier et al. 2015). Changing forest and fire management practices can also impact future fire activity.

Despite these caveats, it was shown that ALL forcing produces an increase in the risk of extreme fire potential compared to NAT forcing alone, using many different metrics. The ALL forcing responses saw longer fire seasons, with more days with significant spread potential and/or conditions suitable for high-intensity fires, and also greater values of the FWI indices designed to represent fuel availability and fire potential. For the majority of these metrics and during the current decade, ALL forcing is estimated to have made extreme fire risk events in the HFR9 region 1.5 to 6 times as likely than would have been the case under only NAT forcings. Thus, the Fort McMurray fire of May 2016 occurred in a world where earlier and longer fire seasons are more likely; where there is an increased risk of extreme fire potential (based on the FWI indices); and a larger number of potential spread days that can result in the growth of a large fire. Many metrics of fire potential showed elevated risk as a result of the combination of natural variability and human emissions.

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This is Exhibit E
referred to in the Affidavit
of Tom Lesiuk #2
sworn before me this 18th day
of December 2018

A Commissioner for taking Affidavits
within British Columbia

5.4 SEA LEVEL CHANGE

5.4.1 PAST AND PRESENT MEAN SEA LEVEL CHANGE

Global mean sea level rose about 21 cm between 1880 and 2012 (Figure 30). The rate of rise (Box 9) increased between the 20th and early 21st centuries. In the 20th century, sea level rose 1.7 ± 0.5 mm/yr, corresponding to about 17 cm over the course of the century while from 1993 to 2003, it rose 3.1 ± 0.7 mm/yr (Bindoff et al., 2007). It has continued at a similar rate to 2009 (Nerem et al., 2010) and in recent years (*see* Figure 30). The sources of sea-level rise include thermal expansion of the upper ocean and melt-water from glaciers, ice caps, and the Greenland and Antarctic ice sheets. Sea level rise is not uniform across the various oceans. Observed global sea-level change has exhibited substantial spatial variability, even over several decades (Meyssignac et al., 2012), mainly due to long-term spatial variability in thermal expansion and changes to salinity. Other effects, such as uneven melt-water redistribution, also contribute to spatial variability.

Much of the Canadian land mass is experiencing uplift due to glacial isostatic adjustment, which is the delayed rebounding of the land surface in response to the removal of the weight of the continental ice sheets during their retreat at the end of the last ice age (Figure 31; Peltier, 2004). The coastlines of Hudson Bay and the central Arctic Archipelago are rising rapidly and have been for thousands of years due to this adjustment, causing sea level to fall. At Churchill, Manitoba, the tide gauge shows sea-level fall of nearly 10 mm/yr since 1940 (Wolf et al., 2006), consistent with a measurement of crustal uplift slightly in excess of 10 mm/yr (Mazzotti et al., 2011).

BOX 9

ABSOLUTE AND RELATIVE SEA LEVEL CHANGES

Global sea-level change is commonly discussed in terms of "absolute" sea level, meaning that it is referenced to the centre of the Earth. At coastal locations, the sea-level change that is observed or experienced relative to a fixed location on land is known as relative sea-level change. Relative sea-level change is the result of absolute sea-level change and vertical land motion, both of which can vary from one location to another. Land uplift decreases relative sea-level rise and land subsidence increases it. In determining relative sea-level changes across Canada, vertical land motion (uplift and subsidence) plays a predominant role, although regional variations in absolute sea-level change are also important.

Outside the area of uplift, the land is sinking at lower rates. The sinking of land is due to the slow flow of rock deep in the Earth's mantle from subsiding regions towards uplifting regions. This reverses the process of flow away from regions depressed by ice sheets in the past. Most of the Maritimes, much of Newfoundland, the Yukon coast, the mainland coast of the Northwest Territories and some of its islands, and the

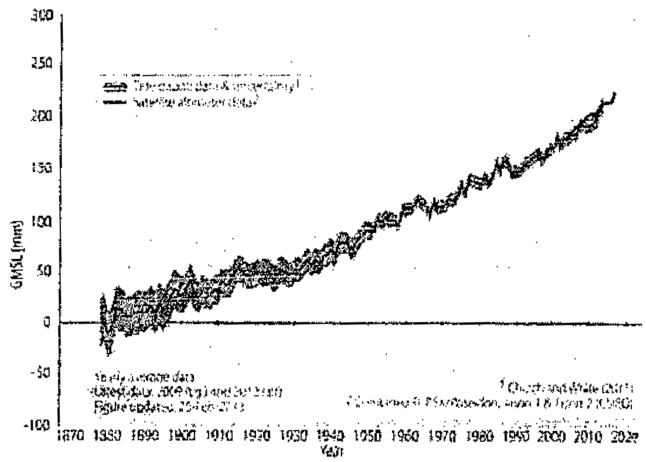

FIGURE 30: Observed global mean sea-level from 1880 to 2012 (*Source: Commonwealth Scientific and Industrial Research Organization [CSIRO], www.cmar.csiro.au/sealevel/ accessed June 17, 2013*). The observations are based on tide gauge data (1880 to 2009) and TOPEX/Poseidon, Jason-1, and Jason-2 satellite altimetry (1993-2012).

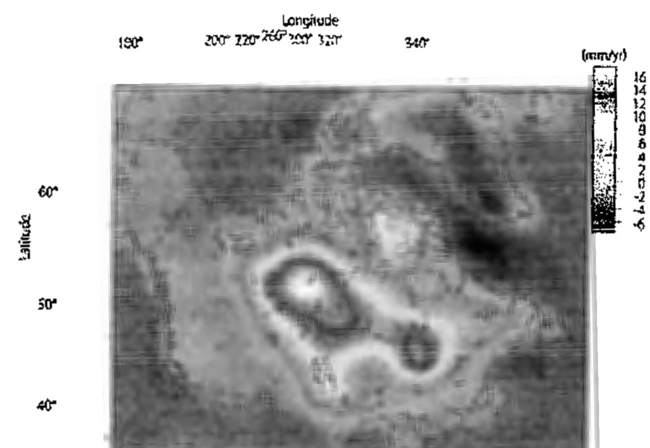

FIGURE 31: Present-day vertical crustal motion (in millimetres per year) predicted by the ICE-5G model of glacial isostatic adjustment (*Source: Peltier, 2004*). Relative sea level is presently falling in regions where the land is rising rapidly, such as Hudson Bay. Areas that are sinking, such as most of the Maritimes, experience relative sea-level rise that is larger than the global value. The model predictions do not include the significant vertical crustal motion in coastal British Columbia caused by active tectonics.

east coast of Baffin Island in Nunavut, are subsiding. These regions have experienced relative sea-level rise over the past few thousand years. At Halifax and Charlottetown, tide-gauge records show that relative sea level has risen at about 3.2 mm/yr throughout most of the 20th century (Forbes et al., 2004, 2009), nearly double the 20th century value of global sea-level rise. At Tuktoyaktuk, on the Beaufort Coast of the Northwest Territories, relative sea-level has risen at 3.5 mm/yr in the past half-century, consistent with a combination of global sea-level rise and local land subsidence (Forbes et al., 2010).

Relative sea-level rise in British Columbia has generally been smaller than in the Maritimes, with differences along the coastline largely arising from vertical land motion due to movement of tectonic plates offshore. The effects of past and present-day mass fluctuations of mountain glaciers and a residual glacial isostatic adjustment effect from the last continental glaciation are also present. In the 20th and early 21st century (1909 to 2006), sea level rose at an average rate of 0.6 mm/yr in Vancouver and Victoria, and 1.3 mm/yr in Prince Rupert, and fell by 0.9 mm/yr in Tofino (Mazzotti et al., 2008).

Another geological factor that contributes to relative sea-level change is sediment compaction. On the Fraser Delta, ongoing subsidence due to sediment compaction has been measured at 1-2 mm/yr (Mazzotti et al., 2008, 2009). Similarly, measurements on the Mackenzie Delta in the Northwest Territories show subsidence of up to several millimetres per year relative to a nearby stable reference point. The additional subsidence of the Delta further contributes to sea-level rise on this isostatically subsiding shoreline (Forbes et al., 2010).

5.4.2 FUTURE CHANGES TO MEAN SEA LEVEL

Global mean sea-level will continue to rise in the 21st century (Figure 32), but there is uncertainty regarding the rate. As projected by the IPCC AR4, the increase in global sea level over the 21st century, relative to the last two decades of the 20th century, would range from 18 to 59 cm depending on the emission scenario (Meehl et al., 2007b). For all scenarios, the thermal expansion component dominated, representing 70 to 75% of the central estimates of the sea level rise by the end of the century (Meehl et al., 2007b). The report also considered that an additional sea-level rise of 10 to 20 cm from accelerated glacier discharge to the oceans could be possible. These results were obtained from process-based models incorporating physical laws and known properties of the atmosphere, oceans, glaciers and ice sheets. Updated projections following the IPCC approach (e.g. Church et al., 2011) indicate a global sea-level rise of about 20 to 80 cm by 2100.

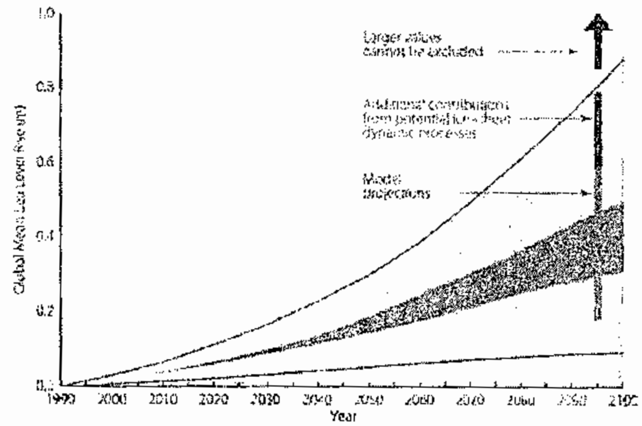

FIGURE 32: Projected global sea-level rise for the 21st century from the IPCC Third Assessment Report (TAR; blue and green shading and red lines; IPCC, 2001) and at the end of the century from the Fourth Assessment Report (AR4; coloured bars; IPCC, 2007). For the TAR, the blue shading shows the variation in the mean projections for a range of emissions scenarios, the green shading shows the range of all model projections, and the outer lines indicate an additional uncertainty from land ice. For AR4, the light red bar shows the range of model predictions, the dark red bar indicates a possible additional contribution from Greenland and Antarctic ice-sheet dynamics, and the dark red arrow shows that larger amounts of sea-level rise cannot be excluded[5] *(modified from Church et al., 2008)*.

Some publications, utilizing semi-empirical methods, suggest larger amounts of global mean sea-level rise by the end of the 21st century, reaching values in excess of 100 cm (e.g. 75 to 190 cm, Vermeer and Rahmstorf, 2009 and 57 to 110 cm, Jevrejeva et al., 2012). The semi-empirical projections are based on assumed relationships between global sea-level and either global temperatures or atmospheric heat balance. They do not capture the full range of physical processes responsible for changes in sea level. At present it is not known why they give higher values of sea-level rise than the process-based modeling which formed the basis of the IPCC TAR (Third Assessment Report) and AR4 (Fourth Assessment Report) results. It has been suggested that the semi-empirical projections be treated with caution owing to a number of limitations (Church et al., 2011).

An upper bound of 200 cm of global sea-level rise by 2100 was derived from glaciological modeling, to help rule out even larger values of global sea-level rise (Pfeffer et al., 2008). Based on an assessment of the probable maximum contributions from various sources of sea-level rise, and on studies using a variety of approaches, a "plausible high-end"

[5] The IPCC recently updated projections of future sea level rise (Stocker et al., 2013) and confirmed that higher levels of sea level rise (>1m) could not be excluded, but assessed the likely (>66% probability) upper end of the range of projected sea level rise to be about 1m relative to current levels by the end of the century.

scenario range of 55 to 115 cm of global sea-level rise by 2100 has been derived for use in flood risk planning (Katsman et al., 2011).

Included in these estimates are the contributions from melting Canadian glaciers and ice caps. The contribution to sea-level rise to 2100 from circumpolar Arctic glaciers is projected to be 5 to14 cm, with Canadian Arctic glaciers, ice fields, and ice caps projected to contribute 1 to 4 cm (AMAP, 2011). A recent update indicates a contribution of 3.5 ± 2.4 cm to global sea-level rise from the Canadian Arctic Archipelago in the 21st century (Lenaerts et al., 2013). Much smaller contributions are expected from western Canadian glaciers given their lower ice volumes (Marzeion et al., 2012).

The patterns of future relative sea-level change in Canada, like past and present-day patterns, will be influenced by land uplift and subsidence, uneven melt-water redistribution, and changes in ocean temperature, salinity and circulation (e.g. Slangen et al., 2012). Around Hudson Bay, some coastlines are rising so quickly that sea-level will continue to fall throughout the 21st century, except for the most extreme scenarios of global sea-level rise (James et al., 2011). A consequence of sea-level fall is reduced depth-under-keel of ocean-going vessels, leading to potential navigation and docking hazards. Areas that are rising more slowly may experience a transition from relative sea-level fall in the early decades of the 21st century to sea-level rise by 2100, depending on the rate of uplift and the amount of global sea-level rise. Subsiding regions will experience enhanced sea-level rise.

Melt-water redistribution in the oceans is uneven (Mitrovica et al., 2001, 2011). The shrinking mass of ice sheets and glaciers reduces their gravitational attraction to water in the oceans, leading to sea-level fall close to a source of meltwater. Near the source of meltwater, the Earth's crust responds elastically to the decreasing load, causing land uplift that also contributes to relative sea-level fall. These processes of meltwater redistribution and elastic crustal response (sometimes termed 'sea-level fingerprinting') are important in Canada because of the presence of Arctic ice caps and, in the west, mountain glaciers and ice fields. In addition, the Greenland ice sheet and Gulf of Alaska glaciers are both sources of meltwater for global sea-level rise. Due to their proximity – on a global scale – to these important sources of melt-water, large regions of Canada will experience reduced rates of relative sea-level rise. The effects of meltwater redistribution are sufficiently pronounced in parts of Arctic Canada that the range of local sea-level projections is less than half the range of global projections (James et al., 2011).

Sea levels are also affected by global ocean circulation, which accounts for greater than 2 m of current spatial variation in absolute sea level. The largest sea level gradient off the coast of Canada is located in the northwest Atlantic where the sea level change across the Gulf Stream is about 1.5m (Thompson et al., 2011). Variability in ocean currents may contribute to sea level change on all three coasts. Above-average sea-level risedue to changes in ocean circulation is projected in the Arctic and the Maritimes (e.g. Yin, 2012; Ezer et al., 2013), partly counteracting the reductions arising from melt-water redistribution. Off the west coast, long-term current-induced changes in coastal sea level may be masked by decadal-scale variations in sea level arising from changes in circulation and upper ocean temperatures associated with major El Niño and La Niña events (Thomson et al., 2008).

Projections of global sea-level rise beyond 2100 have an even larger uncertainty, but indicate continuing global sea-level rise over the coming centuries and millennia (e.g. Katsman et al., 2011; Huybrechts et al., 2011; Jevrejeva et al., 2012). Global sea-level rise may eventually amount to several metres.

5.4.3 EXTREME WATER LEVELS

Rising mean sea levels are an important factor with respect to extreme (high) water levels, which generally occur when storm surges coincide with high tidal levels. Contributions from harbour seiches, wind waves, and interannual and seasonal variability are also important. Ocean-surface heights vary on time scales from years to hours due to atmosphere and ocean variations, such as ENSO, NAO, seasonal warming and runoff, storms, and changes to ocean circulation. In the Pacific, extreme ENSO events can result in coastal sea level changes of a few tens of centimetres. Storm surges can have amplitudes of more than a metre on all three coasts (Bernier and Thompson, 2006; Manson and Solomon, 2007; Thomson et al., 2008). This short-term, large-amplitude variability causes peak water levels to vary substantially throughout the year and from year to year. It is superimposed on the slow rise in mean sea level which causes incrementally higher water levels over time where relative sea level is rising. In the Bay of Fundy, increasing mean sea level is resulting in a small increase in the tidal range due to increased resonance of the semidiurnal tides (Greenberg et al., 2012), which will further contribute to extreme high water levels there.

Climate-related changes in the above factors will also affect extreme water levels in many regions of the globe. Possible climate changes affecting the intensity and frequency of storms, hurricanes and high wind waves are of particular concern, though they are expected to vary geographically and there is uncertainty regarding their sign and magnitude in most areas (e.g. Ulbrich et al., 2009; Harvey et al., 2012; Rummukainen, 2012; Seneviratne et al., 2012). Available analyses of observed wind speed changes at coastal locations around Canada are inconclusive regarding long-term trends (Hundecha et al., 2008; Wan et al., 2010). There are some suggestions that the strongest storms will become more intense in mid-to-high latitude areas of the North Pacific and North Atlantic (e.g. Mizuta, 2012; Woollings et al. 2012), associated with poleward shifts of the jet stream and storm tracks. However, there are differences in the details of the projected changes depending on season and location (e.g. Perrie et al. 2010; Long et al. 2009) and among models.

Changes in sea-ice cover have important implications for wind waves reaching the coast. Nearshore sea ice prevents waves from breaking directly onshore and reduces wave run-up (Forbes and Taylor, 1994; Allard et al., 1998). Ice further offshore reflects waves and reduces the amplitude of waves before they reach the shoreline (Wadhams et al., 1988; Squire, 2007), so that more open water will lead to larger waves even if the winds are unchanged. Thus, where there are projected reductions in sea ice, such as Atlantic Canada and the Arctic, there is the potential for increased extreme water levels due to run-up.

Increased extreme water levels will generally lead to increased amounts of coastal erosion. Dyked areas, coastal regions with little relief, and coastlines comprised of unconsolidated sediments are more vulnerable to erosion than high-lying, rocky coastlines. In the Arctic, increased air and water temperatures may degrade and thaw permafrost, loosening ice-bonded sediments and also contributing to erosion (Forbes, 2011). At this time, it appears that the long-term changes to the frequency and intensity of extreme coastal water levels and flooding in Canada will be primarily driven by changes in mean sea level and by sea ice changes, although tides, storm surge, and waves will continue to play prominent roles. Regions that are projected to experience an increase in mean sea-level are also likely to experience increasing extreme high water levels.

6. SUMMARY

Atmospheric warming has been widespread across Canada since 1950, although strongest in the north and west. It has occurred in all seasons, but has been most pronounced in winter and spring. The primary contributor to long-term warming in Canada (and the rest of the world) since the mid-20th century has been the anthropogenic emission of GHGs. Other factors can strongly influence short-term climate variability imposed on the long-term trend.

A range of indicators provides a coherent picture of the response of the atmosphere-ice-ocean system to this climate warming. An increase in hot extremes and a decrease in cold extremes of air temperature have been observed across the country. Canada as a whole has become wetter, although with notable spatial and seasonal variability. In most of southern Canada there has been a decrease in snowfall and an increase in rainfall consistent with warmer temperatures. A reduction in the spatial extent and mass of the Canadian cryosphere is evident in observations of rapidly declining snow and sea ice cover, shorter seasons of ice cover on many lakes and rivers, widespread warming of permafrost and shrinkage of glaciers in both western Canada and the High Arctic. Indicators of surface freshwater availability, such as streamflow, provide integrated responses to climate and cryospheric change, but spatially consistent patterns across the country are difficult to discern.

Natural climate fluctuations such as El Niño and the North Atlantic Oscillation contribute to regional climate variability on short (decadal) time scales. The warming projected to occur throughout this century will be associated with a continuation and potential acceleration of many of the trends observed over the past half century. Some patterns of change may prevail for Canada as a whole (a warmer, wetter Canada with less snow and ice), but regional and seasonal variability will continue. In particular, amplified warming and related impacts in the Arctic are expected. Precipitation changes are particularly uncertain, but potential declines in southern Canada, combined with warmer summers and increased evaporation, could increase seasonal aridity and reduce freshwater availability in some areas.

Long-term changes in ocean climate – temperature, salinity, oxygen levels and acidity – consistent with increasing atmospheric CO_2 and anthropogenic climate warming have been observed in all three of Canada's oceans. However, natural variability on decadal to multi-decadal time scales has also contributed to the observed changes in some areas (e.g. the Northwest Atlantic) off Canada. Nevertheless, warmer waters, reduced sea ice, reduced upper ocean salinities, and increased vertical density stratification are expected in most Canadian waters over the next century. The observed global trends of ocean acidification and reduced sub-surface oxygen levels are expected to continue and to be evident in Canadian waters as well.

Sea level change along Canadian coastlines has been, and will continue to be, affected by both global and local factors. Expansion of warming waters and increased meltwater from land ice are both contributing to rising global sea levels. Estimates of the magnitude of future changes in global sea level by the year 2100 range from a few tens of centimetres to more than a metre. Vertical land movement strongly influences relative sea level changes at the local scale. Where the land is currently subsiding, such as most of the Maritimes, relative sea level is rising at rates larger than the global average, and will continue to rise. Where the land is rising rapidly (e.g. around Hudson Bay), sea level will continue to fall except under extreme scenarios of sea level rise. Areas where land is rising more slowly may see a transition from relative sea level fall to relative sea level rise over the 21st century. Extreme sea levels are likely to be experienced more frequently in the coming century where relative sea level is rising and where sea ice is projected to decrease in the Arctic and in Atlantic Canada.

ACKNOWLEDGEMENTS

The authors would like to thank the following colleagues who reviewed and offered constructive comments on chapter drafts: John Fyfe and Xuebin Zhang of Environment Canada, Kumiko Azetsu-Scott, Diane Lavoie, Charles Hannah and Rick Thomson, of Fisheries and Oceans Canada, and Don Forbes and Joseph Henton of Natural Resources Canada. We would also like to express our gratitude to the anonymous external reviewers for their time and efforts.

This is Exhibit F
referred to in the Affidavit
of Tim Lesiuk #2
sworn before me this 14th day
of December 2018

A Commissioner for taking Affidavits
within British Columbia

SQUAMISH - LILLOOET REGIONAL DISTRICT

Village of PEMBERTON

For immediate release
January 18, 2018

MOUNT CURRIE LANDSLIDE RISK ASSESSMENT COMPLETE:

Determines low probability of a large impact event; community information meetings scheduled for January 24th and 25th

Pemberton, BC – Local Officials have received the results of the Mount Currie Landslide Risk Assessment ("the Assessment"), conducted by BGC Engineering Inc. (BGC). BGC was engaged to determine landslide and associated flood risk from the north face of Mount Currie Mountain including risk to life, buildings, critical facilities, business activities, power and communication lines. The Assessment was prompted by an increase in observed small rockfall events during the summers of 2015 and 2016, which raised concerns about the potential risk to the communities below the north face of Mount Currie. The completed Assessment has confirmed areas of instability that could result in small rockfall events and rare but large-scale rock slope failures.

Elected Officials from Lil'wat Nation, SLRD and Village of Pemberton (Village) met today to review the report with BGC engineers and have agreed to continue joint advocacy efforts to secure funding for further studies and monitoring systems, as recommended by the Assessment. On a staff level, Emergency Program Managers from all three jurisdictions will integrate this new information into existing Emergency Management plans.

According to the BGC analysis, up to nineteen potential rock avalanche source zones exist, with four being identified as having high hazard potential. Two of those four zones, known as Scenario 1 and 2 (see enclosed map) were identified as having the potential for rock avalanches large enough to travel north of the Green and/or Lillooet Rivers. In these two scenarios, the rockfalls are predicted to travel over 100km/hour and involve volumes up to approximately 8 million cubic metres of material.

Associated damming of the Green and Lillooet Rivers was also assessed; approximately 160 buildings within the study area were identified as having a higher vulnerability (greater than 1m flow depth above the estimated first floor elevation), should Scenario 2 occur.

Geoscientists have calculated that the annual probability of the modeled rock avalanche of Scenario 1 is approximately a 0.02% chance of occurrence in any given year, while the annual probability of the modeled rock avalanche of Scenario 2 is a 0.009% chance of occurrence in any given year, under current conditions and current weathering and erosion rates. For comparison, the probability is similar to the estimated probability of large debris flows from Mount Meager (Friele et al. 2008).

Mount Currie's stability is believed to be influenced, in part, by the assumed existence of permafrost. With climate change, the report concludes that permafrost will degrade and the ice presumed to be present will melt. This would imply a higher frequency and possibly higher magnitude of rock slope failures in the future.

Due to Mount Currie's size and the number of source zones for rock avalanches, the Assessment states that engineered mitigation options are not practical. As a result, BGC has recommended monitoring as the most practical and cost-effective approach to risk management. The Assessment also recommends that land use be restricted in part or all of the areas modeled for rock avalanches, as any increase in development density would increase the population at risk.

The full report is available for download from the following websites:

- Lil'wat Nation (www.lilwat.ca)
- SLRD (www.slrd.bc.ca)
- Village of Pemberton (www.pemberton.ca)

Community information sessions will be held in Pemberton and Lil'wat Nation:

- **Wednesday, January 24th from 6:30-8:30pm at the Pemberton & District Community Centre, and**
- **Thursday, January 25th from 6:30-8:30pm at the Ull'us Community Complex.**

Community members are encouraged to attend either meeting. Each information session will begin with a presentation of the Assessment findings by BGC engineers, who will also be available to answer questions. To ensure that as many questions as possible can be answered at these sessions, community members are encouraged to review the Assessment in advance and submit their questions prior to the community information meetings to one of the community contacts noted below:

- Lil'wat Nation: Sylvia Dan (Sylvia.dan@lilwat.ca)
- SLRD: Sarah Morgan (smorgan@slrd.bc.ca)
- Village of Pemberton: Jill Brooksbank (admin@pemberton.ca).

The Mount Currie Landslide Risk Assessment was funded provincially through Emergency Management BC (EMBC) and overseen by a steering committee composed of representatives from the SLRD, Village, Lil'wat Nation, the Ministry of Forests Lands and Natural Resource Operations and Rural Development (MFLNRORD) and EMBC.

Quotes

"We have existed on these lands, with the very potential for natural disaster impacts, all our lives in this valley. We live between two rivers that are annually very active in their natural high and low flows. The mountains are no different in their actions and have been very active in the recent years. I feel that we are responsible to our community members to communicate all information that pertains to their safety and wellbeing, which includes the steps of inquiry and applications of professional advice that we have undertaken collaboratively with our neighboring communities." **– Dean Nelson, Political Chief, Lil̓wat Nation**

"This Assessment has given us a more complete understanding of the risks related to rock avalanches on Mount Currie, and it will help all of our organizations with future land use and emergency management planning. We are grateful to the Province of BC for making this study possible, and we look forward to working with our local, provincial and federal partners as we explore further studies and monitoring options to keep our communities safe." **– Jack Crompton, Board Chair, Squamish-Lillooet Regional District**

"We understand this new information is concerning, however we now have a better understanding of the potential risks and we can plan accordingly. The Village will integrate this new information info existing emergency management plans, and consider this information during our Zoning Bylaw update. The Village, with our partners, will continue joint advocacy efforts to secure funding for monitoring systems and further studies. As we learn more about the dynamic characteristics of Mount Currie, we will continue to share this information with our communities." **– Mike Richman, Mayor, Village of Pemberton**

-30-

About Mount Currie Mountain

Located within Lil'wat Traditional Territory, Mount Currie Mountain, also known as Ts'zil in Ucwalmicwts, is a spectacular 2,591 m (8,501 ft.) peak overlooking the Pemberton Valley. Mount Currie is Crown Land that falls within Electoral Area C of the Squamish-Lillooet Regional District and situated between Lil'wat Nation and the Village of Pemberton. Mount Currie is the northernmost summit of the Garibaldi Ranges in southwestern British Columbia.

About the Squamish-Lillooet Regional District (SLRD) | www.slrd.bc.ca

Located in southwestern BC, the Squamish-Lillooet Regional District (SLRD) is a local government federation consisting of four member municipalities (the District of Lillooet, the District of Squamish, the Village of Pemberton and the Resort Municipality of Whistler) and four unincorporated, rural electoral areas (A, B, C, and D). Headquartered in Pemberton, which is the approximate geographic centre of the region, the SLRD delivers a wide range of local, regional and sub-regional services to approximately 43,000 residents.

About Lil'wat Nation | www.lilwat.ca

The majority of Lílwat Nation citizens live near beautiful Mount Currie, British Columbia. The community is home to the majority of the nation's more than 2,000 members. The people of the Lílwat Nation are engaged in all economic sectors while continuing to celebrate, and engage in, traditional ways. Fishing, hunting and harvesting indigenous plants for food and medicine are among the cultural practices that have endured since time immemorial. The Lílwat Nation's Traditional Territory boundaries extend south to Rubble Creek, north to Gates Lake, east to the Upper Stein Valley and west to the coastal inlets of the Pacific Ocean. This 791,131 ha of land occupies a transition zone that goes from temperate coastal environment to the drier interior of British Columbia.

About the Village of Pemberton | www.pemberton.ca

Pemberton is one of the most desirable communities in BC and home to family farms, fresh outdoor adventures and stunning vistas. With over 2,400 residents and just 30 km from Whistler, Pemberton prides itself on its creative and collaborative approach with the business community, local volunteer groups, neighbouring communities and key business and tourism partners such as Tourism Pemberton and the Pemberton & District Chamber of Commerce. Pemberton's mild winters, warm summers and unique pioneer heritage provide an ideal place to enjoy arts, culture, history, recreation, dining, shopping and comfortable lodging.

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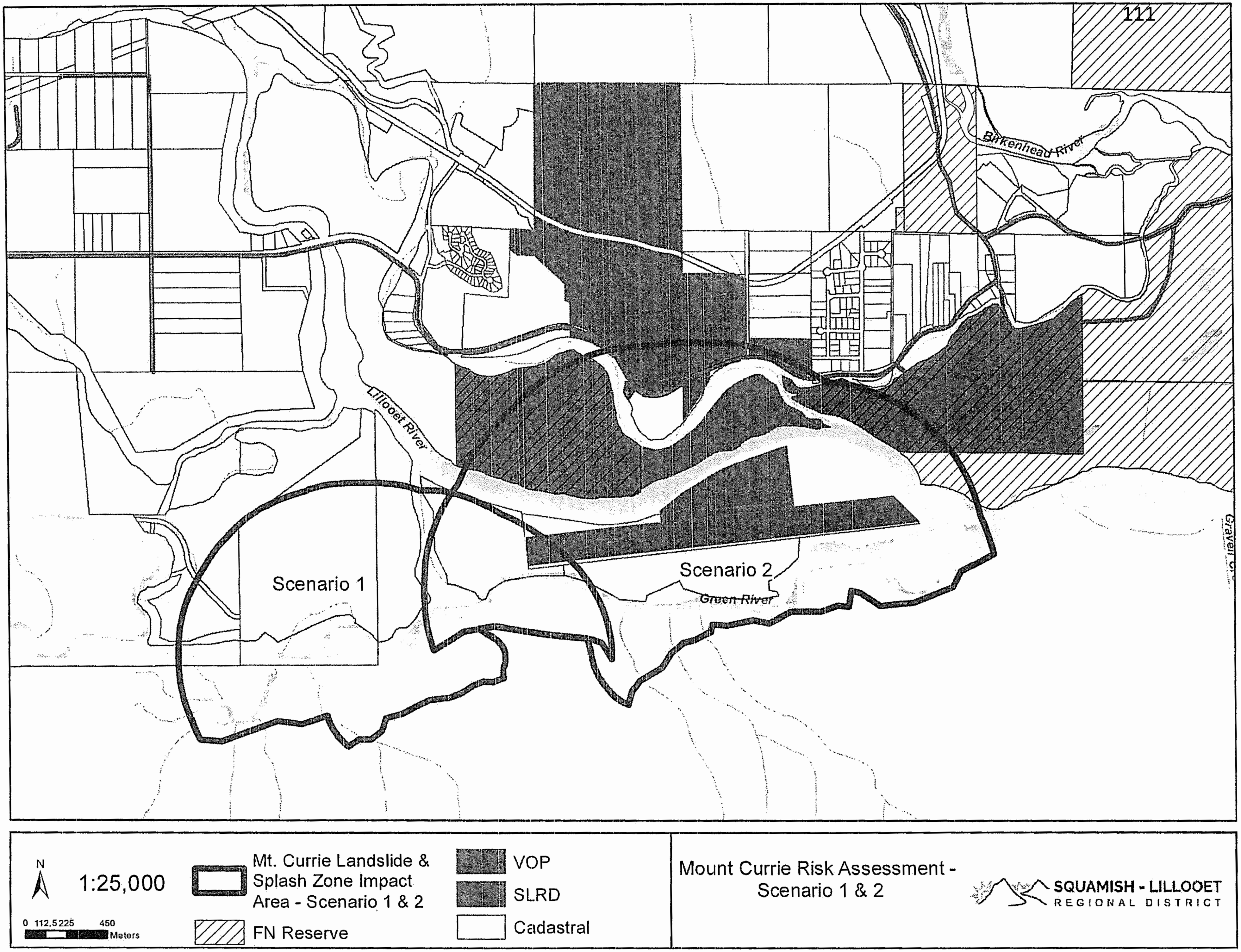
Birkenhead River
Lillooet River
Scenario 1
Scenario 2
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Mt. Currie Landslide & Splash Zone Impact Area - Scenario 1 & 2
FN Reserve
VOP
SLRD
Cadastral
Mount Currie Risk Assessment - Scenario 1 & 2
SQUAMISH - LILLOOET REGIONAL DISTRICT

PLOS | ONE

This is Exhibit G referred to in the Affidavit of Tim Leslie #2 sworn before me this 19th day of December 2016

A Commissioner for taking Affidavits within British Columbia

RESEARCH ARTICLE

Effects of Ocean Acidification on Temperate Coastal Marine Ecosystems and Fisheries in the Northeast Pacific

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Data Availability Statement: Fig. 1: Saltwater finfish and hatchery sites and commercial marine shellfish farms (referenced in Figure caption) are available at: https://apps.gov.bc.ca/pub/geometadata/. R code used to make the figure is available as a Supporting Information file titled S1 Code. Fig 2: Values of PCO2 and pH are calculated from published data (refs 27 and 40). We include these data in the R code used to make the figure in S2 Code. Fig. 3: We include the data used to make this figure—S1 Data—and the R code used to make this figure—S3 Code—as supporting information. Fig. 4: Landed values are

Abstract

As the oceans absorb anthropogenic CO_2 they become more acidic, a problem termed *ocean acidification* (OA). Since this increase in CO_2 is occurring rapidly, OA may have profound implications for marine ecosystems. In the temperate northeast Pacific, fisheries play key economic and cultural roles and provide significant employment, especially in rural areas. In British Columbia (BC), sport (recreational) fishing generates more income than commercial fishing (including the expanding aquaculture industry). Salmon (fished recreationally and farmed) and Pacific Halibut are responsible for the majority of fishery-related income. This region naturally has relatively acidic (low pH) waters due to ocean circulation, and so may be particularly vulnerable to OA. We have analyzed available data to provide a current description of the marine ecosystem, focusing on vertical distributions of commercially harvested groups in BC in the context of local carbon and pH conditions. We then evaluated the potential impact of OA on this temperate marine system using currently available studies. Our results highlight significant knowledge gaps. Above trophic levels 2–3 (where most local fishery-income is generated), little is known about the direct impact of OA, and more importantly about the combined impact of multi-stressors, like temperature, that are also changing as our climate changes. There is evidence that OA may have indirect negative impacts on finfish through changes at lower trophic levels and in habitats. In particular, OA may lead to increased fish-killing algal blooms that can affect the lucrative salmon aquaculture industry. On the other hand, some species of locally farmed shellfish have been well-studied and exhibit significant negative direct impacts associated with OA, especially at the larval stage. We summarize the direct and indirect impacts of OA on all groups of marine organisms in this region and provide conclusions, ordered by immediacy and certainty.

available publicly from http://www.env.gov.bc.ca/omfd/reports/Seafood-YIR-2011.pdf (ref 34) and (for euphausiids) from http://www.pac.dfo-mpo.gc.ca/im-gp/mplans/2013/krill-sm-2013-17-eng.pdf (ref 39). We include the data in the R code used to make this figure in S4 Code.

Funding: The authors were funded by Fisheries and Oceans Canada through the Inter-Governance Strategy (IGS) funding. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

Introduction

Fossil fuel burning and changes in land use by humankind have increased atmospheric carbon dioxide (CO_2) at an unprecedented rate, causing our climate to change [1]. A significant portion of this anthropogenic CO_2 ($\sim 30\%$; [2]) has been absorbed by the ocean. When CO_2 enters the ocean it combines with water (H_2O), resulting in an increase in the concentration of hydrogen ions [H^+] and an increase in acidity (decrease in pH [3, 4]. Therefore, as our climate changes, our oceans become more acidic due to anthropogenic contributions, a problem termed Ocean Acidification (OA) [5].

While anthropogenic atmospheric CO_2 dominates contributions to OA on a global scale, other anthropogenic sources may be significant on a local scale [6]. For example, acid rain from vehicle emissions and industry cause an increase in ocean acidity, which is likely relevant, at least near (and downwind of) urbanized regions [7]. Any addition of organic carbon to the ocean, such as sewage, decomposes to dissolved inorganic carbon (DIC), and increases acidity. Agricultural run-off provides nutrients which then fuel (an anthropogenic) increase in production of organic carbon in the ocean [8], again increasing acidity.

Aquatic acidity is most commonly reported as pH. However, pH is difficult to determine accurately in saltwater because of the additional ions present in solution [9]. It is closely linked with carbonate chemistry in the ocean, which is complex. To quantify the *carbon state* (*i.e.* the concentration of each chemical form of DIC present) in seawater, two of four measured parameters—DIC, pH, total alkalinity (TA), and partial pressure of CO_2 (P_{CO2})—must be known, in addition to temperature and salinity. To be more accurate, phosphate and silicic acid concentrations are also required [10]. In the past, pH has most often been determined from DIC and TA (*e.g.* [11]). (TA is the acid neutralizing capacity of the solution, which is not simply related to pH in seawater [10].) Thus, although one can generalize to say that high DIC is usually associated with low pH (or high P_{CO2}), more information, *e.g.* TA, is required to be quantitative.

The carbon state is relevant to biology. Most of the DIC in the ocean occurs in the form of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}), with less than 1% in the form of CO_2. When pH decreases, the balance between HCO_3^- and CO_3^{2-} changes so that there is less CO_3^{2-}. This shift has important implications for plants and animals that build calcium carbonate ($CaCO_3$ structures (*e.g.* shellfish, corals) [12]. Two mineral forms of $CaCO_3$ (aragonite and calcite) are common in biological structures. The aragonitic form is more soluble than calcite given the same environmental conditions [13]; therefore, creatures that use aragonite are more susceptible to OA than those that use calcite [12]. The ease with which these minerals are formed is quantified by the saturation state (Ω), such that as Ω decreases, dissolution increases [14]. The water is *undersaturated* with respect to $CaCO_3$ when the chemical rate of dissolution exceeds the rate of formation [15]. For organisms that precipitate $CaCO_3$, decreasing Ω means that more energy is required to build and maintain their carbonate structures [16, 17].

Marine organisms are also affected by carbon state (defined above) and OA in other ways. All marine animals need to rid themselves of metabolically produced CO_2 through respiration. The effectiveness of this removal is dependent, in part, on the ambient P_{CO2} of the medium (*e.g.* [18]). Similarly, plants and animals rely on pH to regulate ion transport, and the energy they must expend to maintain intra- and extracellular pH depends on ambient pH (*e.g.* [19]). Thus, there is no one carbon parameter that best indicates OA impacts on all marine organisms, and so full knowledge of the complete carbon state is desirable (*e.g.* [20]).

A large and growing number of studies have been undertaken regarding OA (S1 Table). To understand and predict biological impacts, an increasing number of experiments have been completed that attempt to emulate future ocean conditions in the laboratory. Experimental conditions are usually defined by controlling either the P_{CO2} or the pH (*e.g.* S2 Table) and recently an internationally accepted guide has been published that describes the techniques used [21]. In most of these experiments, present-day conditions (the control) are set at either atmospheric P_{CO2} (~400 μatm at the time of writing) or the estimated current global average pH of the surface ocean, which is 8.1 [5]. However, marine organisms in the natural environment may experience values that are significantly different depending on location and the depth that they occupy.

In the ocean, DIC (and P_{CO2}) generally increase with depth while pH decreases. In other words, low pH conditions naturally occur at depth. This partitioning of inorganic carbon towards deeper parts of the ocean is due in large part to the 'biological pump' that allows the ocean to hold more carbon [22]. Photosynthesis in the surface draws down DIC (which increases pH) and produces organic forms of carbon. Some of this organic carbon falls to deeper levels, where it decays back to DIC (decreasing pH).

British Columbia—oceanography

British Columbia (BC) makes up 27,000 km (17,000 mi) of the temperate northeast Pacific coastline. Circulation along this coast (Fig. 1) is dynamic so that large changes in carbon parameters occur both in space (*e.g.* [23]) and time (*e.g.* [24, 25]). Coastal upwelling along the west coast of Vancouver Island (WCVI) [26] brings subsurface water high in DIC into the surface mixed layer [27] so that low pH (*e.g.* 7.6) is found at relatively shallow depths, *e.g.* above 125 m (Fig. 2). Furthermore, these subsurface waters are enriched in DIC relative to waters at the same depth in other ocean basins, simply because north Pacific water is relatively 'old' and has had more time to receive organic matter [28, 29]. Upwelled waters are also rich in nutrients that are limiting to phytoplankton growth and so cause high primary production that increases pH at times. In fact, the WCVI enjoys the highest productivity of any zone on the northeast Pacific coast [30]. Consequently, present-day ranges in pH in the surface mixed layer along the outer BC coast span a remarkable range (7.8–8.4; Fig. 2). The low end of this range is significantly lower than the benchmark of present-day average global surface ocean pH (8.1).

In protected waters (*e.g.* Strait of Georgia, Fig. 1) less data are available relative to the WCVI. These data show similar (or larger) ranges in surface pH and P_{CO2} (unpublished data, DI), which are also similar to values found just to the south in the protected waters of Puget Sound, Washington State (WA) [6, 31]. Again, a critical feature in these waterways is low surface pH (high P_{CO2}) relative to global averages, especially during the winter season [32].

British Columbia—fishery

Fisheries and aquaculture play an important role in the BC economy, contributing over $650 million (we quote all dollar values in Canadian dollars) to the provincial gross domestic product (GDP) in 2011 [33]. Sport (or recreational) fishing, mainly for salmon and Pacific Halibut, is responsible for approximately 50% of this contribution, while the wild (or capture) fishery makes up ~15% and aquaculture ~10%. Marine ecosystems also play critical cultural roles in BC and their monetary value to tourism is only partially included in these totals (through sport fishing).

Over the past 20 years the wild fishery has declined in terms of both its contribution to the BC GDP and employment, although some individual components are increasing (*e.g.* prawns, Geoduck Clam, Pacific Halibut). Meanwhile aquaculture has nearly tripled its contribution to BC GDP in the same time frame [33]. As a result, published landed values associated with aquaculture are about the same as those from the wild fishery (see Results) and aquaculture now employs slightly more people than does the wild fishery [33].

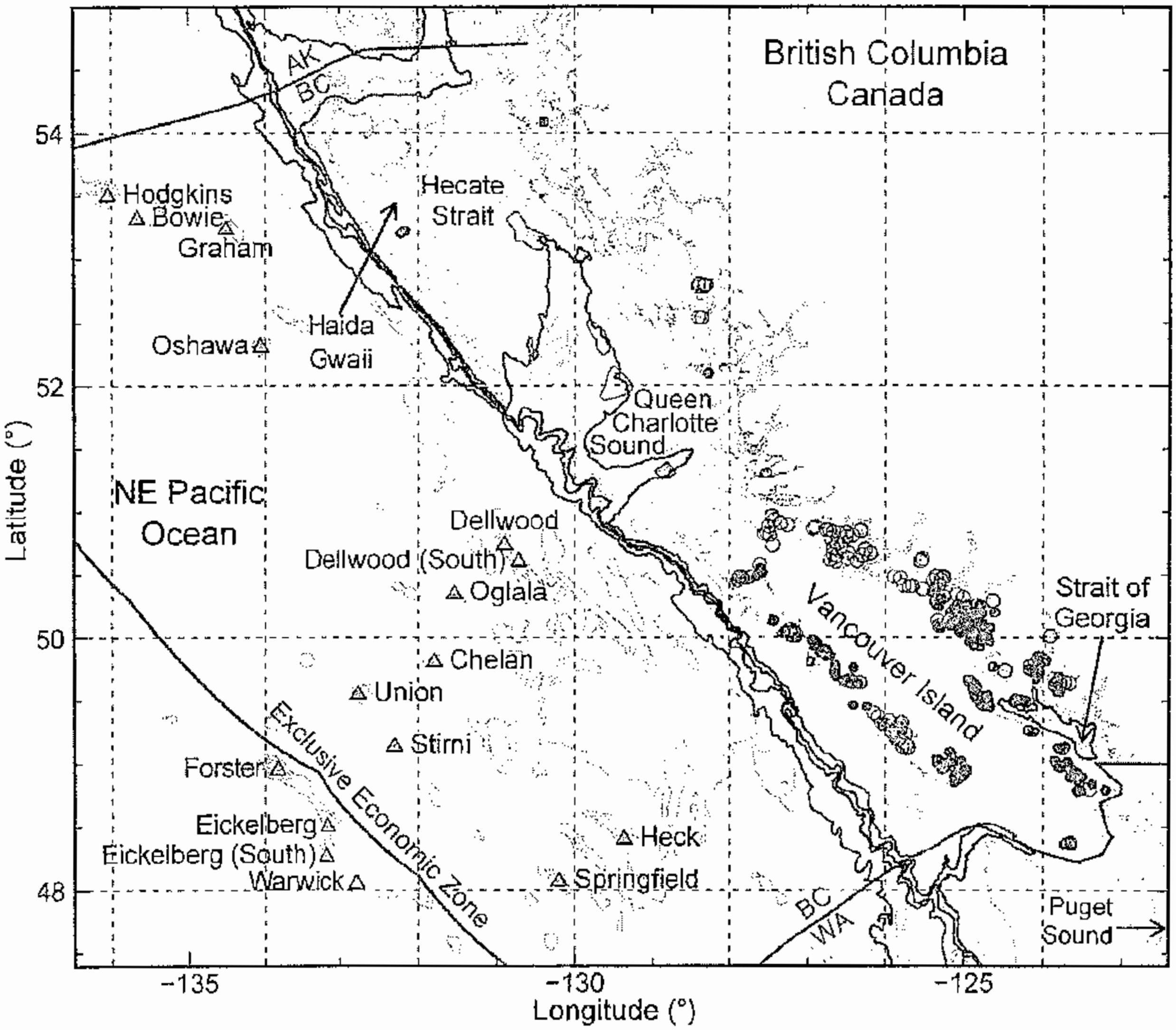

Fig 1. British Columbia (BC) coastline and bathymetry (isobaths in metres: thin grey—100, 200, 300, . . ., 1000, 1250, 1500, 2000, 2500; thick blue—200, 500, 800, and 1600). The continental slope along most of BC comprises steep slopes, especially along the west coasts of Haida Gwaii and northern Vancouver Island. Hecate Strait is largely dominated by shallow waters and a flat seafloor. Sponge reef core protected areas in Hecate Strait and Queen Charlotte Sound are shaded pink. The Strait of Georgia forms a large inland sea that is heavily influenced by river runoff and tidal currents. Saltwater finfish farm and hatchery sites are indicated by open red circles, commercial marine shellfish farms are indicated by solid green circles [345]. Select seamounts [346] are marked by blue triangles. Canada's Exclusive Economic Zone (200-nautical miles offshore) is delimited in red. Map was prepared using PBSmapping in R [347]. The R code is provided as Supporting Information (S1 Code).

doi:10.1371/journal.pone.0117533.g001

The wild fishery is for the most part associated with the open coast (outer WCVI and Queen Charlotte Sound, Fig. 1) and is relatively diverse, with no one fishery dominating landed values (see Results). The most important contributors (Pacific Halibut, Geoduck Clams, prawns, crabs, tunas, Sablefish, rockfishes) currently each have landed values in the $20–50 million range [34]. Aquaculture occurs in protected waters: shellfish farming mainly in the northern Strait of Georgia and finfish farms and hatcheries mainly north of that on the north-eastern side of Vancouver Island (Fig. 1). In BC, Atlantic Salmon aquaculture clearly dominates all other commercial fisheries (see Results).

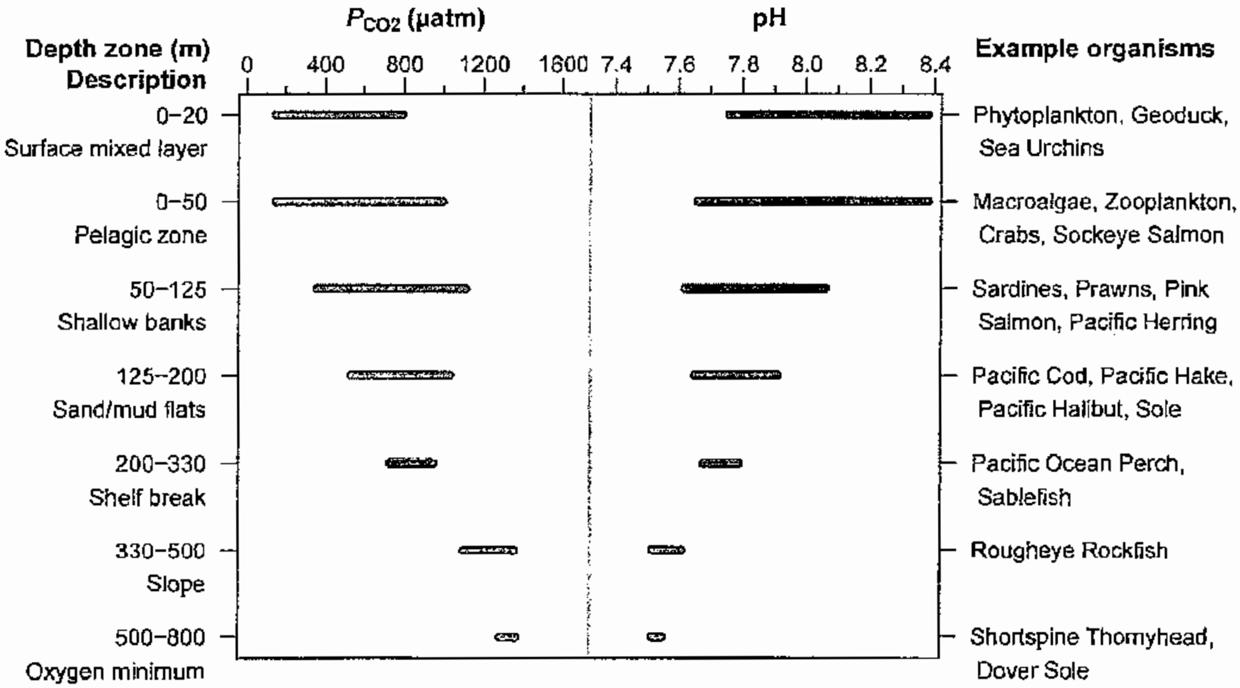

Fig 2. Estimated present-day ranges of P_{CO2} (red) and pH (blue) during spring [40] and summer [27] for various depth zones along the outer BC continental shelf, with typical species found in each zone (see Methods). There are numerous data above 50m and few below 125 m. The number of values in each depth zone from top to bottom are: 70, 116, 33, 45, 5, 4 and 2, respectively. Above 50 m, the distributions of values are skewed, such that high P_{CO2} (low pH) extremes occur less often than the low P_{CO2} (high pH) extremes. Data and R code for this figure are provided as Supporting Information (S2 Code).

doi:10.1371/journal.pone.0117533.g002

Predicting biological impacts due to OA is a highly complex problem that has only become a concern relatively recently (primarily over the past decade). There have been excellent review papers outlining anticipated impacts on a general global scale (*e.g.* [3, 35]) as well as meta-analyses of existing work on the topic (*e.g.* [36]). Cooley and Doney [37] have provided the first estimate of the economic impact of OA, centred on the shellfish fishery, in the United States. However, few studies consider specific ecosystems, particularly in the context of local pH conditions and natural variability, and none focus on the temperate northeast Pacific.

Here, we examine the potential impact of OA on temperate coastal ecosystems in the northeast Pacific Ocean, with a focus on BC fisheries. To tackle this issue we:

- describe the current marine ecosystem in BC (especially by depth, Fig. 3);
- define the present-day carbon state with depth in local waters (Fig. 2);
- assess the response by marine organisms in this region to OA by investigating existing biological OA impact studies (on local and non-local species) and comparing anticipated changes in acidity (P_{CO2}) to those currently experienced along the BC coast.

We use the best information available at present to address this problem. The quantitative details, including treatments and measured carbon parameters, of all studies that we used are summarised in S2 Table. We provide specific conclusions ordered by immediacy and relevance to the BC fishery.

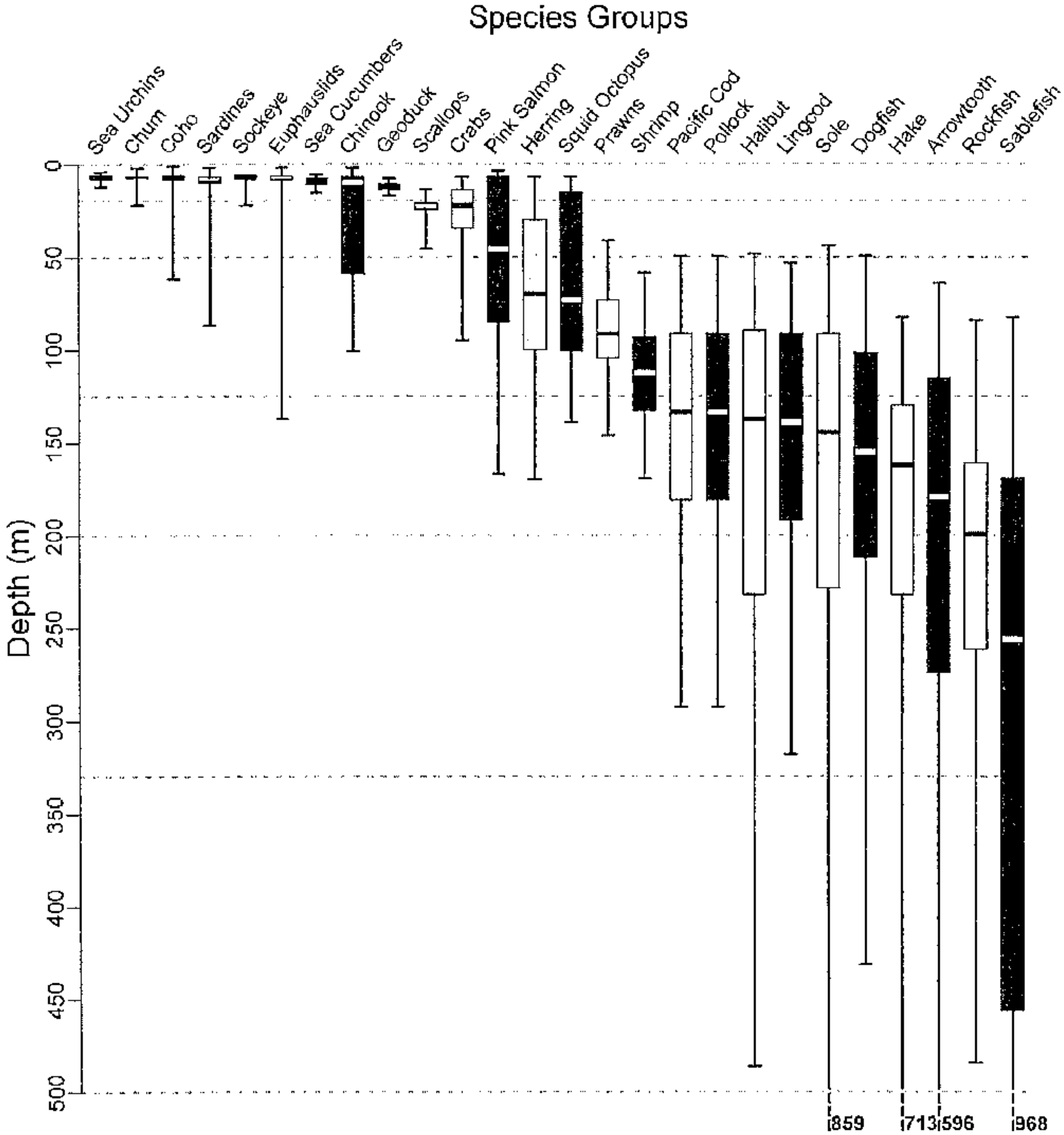

Fig 3. Depth-of-capture, expressed as quantile box plots of depth (m), from fisheries and survey data (where available) for species groups identified in Fig. 4. For each quantile box, the upper whisker, box top, box delimiter (horizontal line), box bottom and lower whisker correspond to the 0.025, 0.25, 0.5, 0.75, and 0.975 quantiles, respectively. Depth quantiles that lie deeper than the figure limit are indicated along the bottom. Horizontal dashed lines correspond to depth zones in Fig. 2. See Methods for data sources. Data and R code for this figure are provided in Supporting Information (S1 Data and S3 Code, respectively).

doi:10.1371/journal.pone.0117533.g003

Methods

Present state of the BC marine ecosystem

Marine organisms were assigned to taxonomic groups and sorted by trophic levels adapted from model-derived output for the BC shelf [38] (Fig. 4). We added several taxonomic groups that are commercially fished [34] (*e.g.* sardine, tuna) and unfished (*e.g.* seagrasses, glass sponges) to this list as necessary. To evaluate species abundance and distribution within these groups, we used published literature (both primary and secondary as cited) where available. When literature was not available we consulted Canadian Department of Fisheries and Oceans (DFO) databases and the expertise of individuals active in the field (see Results and *Acknowledgements*). Landed values of fished species were taken from [34] (or [39] for euphausiids).

Species depth distributions (Fig. 3) were obtained from DFO databases (Pacific Biological Station, Nanaimo, Canada). Depths associated with commercially-caught groundfish (compiled by RH, May 1, 2014) and shellfish (compiled by Georg Jorgensen, May 6, 2014) are depths-at-capture, most often a mean of the minimum and maximum depths of fishing events (usually trawl or trap). For the commercial species groups (Fig. 4), depths were selected based on fishing methods specific to each group—Sea Urchins (dive), Euphausiids (nets), Sea Cucumbers (dive), Geoduck Clam (dive), Scallops (dive, trawl), Crabs (trap), Squid & Octopus (dive, trap), Prawns (trap), Shrimp (trawl), Pacific Cod (midwater & bottom trawl), Pollock (midwater & bottom trawl), Halibut (bottom trawl), Lingcod (bottom trawl), Sole (bottom trawl), Dogfish(bottom trawl), Hake (midwater trawl), Arrowtooth (bottom trawl), Rockfish (midwater & bottom trawl), Sablefish (bottom trawl). Depths associated with pelagic species (Herring, Sardines, and Salmon—Chinook, Chum, Coho, Sockeye, Pink) come from two sources: the WCVI Sardine Trawl Survey (spanning the WCVI, Fig. 1: −129.14°W to −124.56° W, 48.32°N to 51.14°N), which occurs mid-summer and is conducted during the night (data compiled by Linnea Flostrand, May 8, 2014), and the La Perouse Survey (spanning the BC coast, Fig. 1: −132.89°W to −123.07°W, 43.58°N to 54.64°N), which is a daytime acoustic trawl survey used to verify acoustic targets (data compiled by Jennifer Boldt, May 14, 2014). The two surveys did not capture any SARA-listed species. Mean depths-of-capture are summarised by quantile boxplots where the box represents 50% of the observations, and the region between the whiskers represents 95% (Fig. 3).

Commercial fishing in Canada is regulated by the *Fishery Act*. Specifically, Section 22 (http://laws-lois.justice.gc.ca/eng/regulations/SOR-93-53/page-6.html) identifies all license conditions that DFO uses to manage gear, monitoring, reporting, harvesting, allocation, and catch requirements. DFO's Pacific Region Animal Care Committee requires animal-use protocols (Supplementary S1 text), but specifically exempts lethal sampling of fish and invertebrates for stock assessment and sampling from commercial operations where animals are dead or certain to die. Data used here were collected for stock assessments and are therefore exempt from protocols.

Local inorganic carbon distributions

Published inorganic carbon data (DIC, TA) from the outer BC coast in Queen Charlotte Sound (QCS) [40] and along the WCVI [27, 40] (Fig. 1) are used. These data (174 discrete samples) were collected over the continental shelf, slope and offshore, from the surface to 800 m with greater depth resolution in the top 50 m. The carbonate system was defined from TA and DIC (CO2SYS, [41]) and the constants of [42] with conductivity, temperature, depth and nutrient data that were collected concurrently. These data were sorted into depth intervals defined by local bathymetry relevant to local marine organisms (Fig. 2).

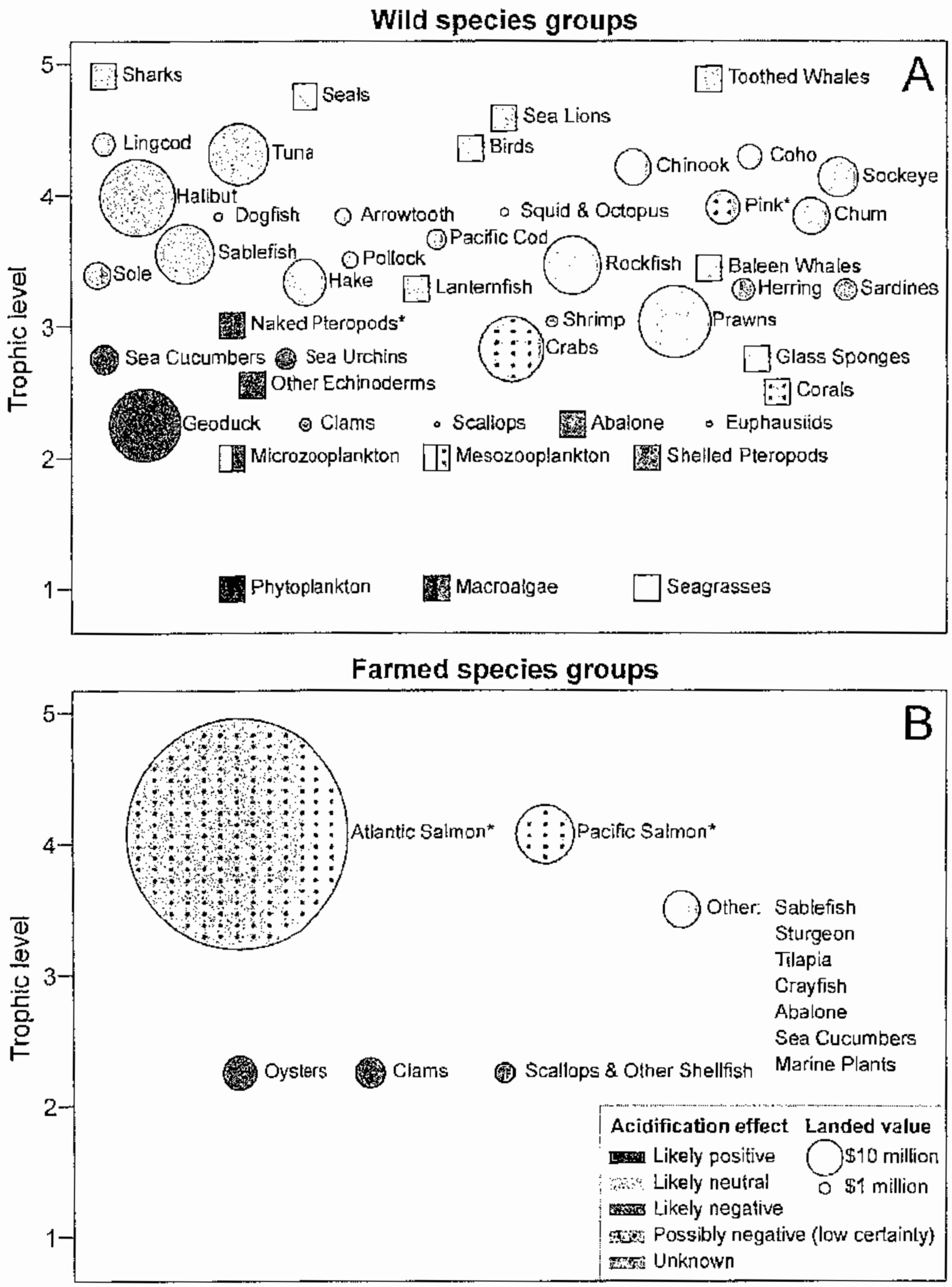

Fig 4. Summary of ocean acidification effects on (A) wild, and (B) farmed species groups in BC waters, including landed value for those that are fished or farmed. Species groups are arranged vertically by trophic level, adapted from output by Preikshot [38] (courtesy of D. Preikshot, Madrone Environmental Services, Duncan BC). Areas of circles are proportional to the landed values in 2011, based on data in [34] (and [39] for euphausiids). Squares represent species groups that are not commercially harvested. Solid colours represent the likely direct effects of ocean acidification (see Results for explanations). Stippling refers to possible effects. For species marked by an asterisk (*), colours represent indirect effects. Data and R code for this figure are provided as Supporting Information (S4 Code).

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Responses of marine organisms to OA

We evaluated the potential impact (coded by colour in Fig. 4) of OA on each taxonomic group that occurs in BC, recognizing that uncertainty exists. We also identified the depth distributions that these groups of species occupy, along with associated OA conditions (Fig. 3). Similar to our description of the local marine system, we used published literature where available to assess direct and indirect effects of OA on taxonomic groups. When no publications were available in this rapidly emerging field, we consulted individuals who presented at recent conferences (in particular *2014 Ocean Sciences Meeting*, Honolulu HI and *2014 Salish Sea Ecosystem Conference*, Seattle WA), and we consulted many other experts in their respective fields (cited within Results and *Acknowledgements*).

Results

There are relatively few published carbon data in BC waters. We use these data [27, 40] to estimate present-day ranges in pH and P_{CO2} for depth intervals relevant to local marine organisms (Fig. 2). We then defined three relative P_{CO2} levels, which are based on the present-day ranges in Fig. 2, to group the experimental treatments presented in the literature relative to our local waters (Table 1). For example, Pink Salmon (*Oncorhynchus gorbuscha*) generally occupy depths in both the 0–50 m and the 50–125 m zone (Fig. 3) so for these fish present-day P_{CO2} in our region is ~200–1000 μatm (pH ~7.6–8.4) (Fig. 2) so that a P_{CO2} level of 5000 μatm would be the upper limit of an 'elevated' (Table 1) treatment.

Vertical distributions of marine organisms on the BC coast are presented with associated impacts of OA, ordered by trophic level (Fig. 4) in the following sections. Depending on trophic level and group, the amount of information available was variable. For many commercially harvested groups (represented by circles in Fig. 4) excellent data were available (*e.g.* finfish, Fig. 3). On the other hand, abundance and species composition of unfished groups are not well characterised, particularly at lower trophic levels (squares in Fig. 4, *e.g.* microzooplankton, corals). For many organisms important in the region, no published OA related studies exist (grey circles and squares in Fig. 4). Where necessary, we have adopted results from OA studies on species elsewhere that are similar to the ones found locally. These caveats are detailed in each section. Experimental details are summarised in S2 Table.

Phytoplankton

In the coastal northeast Pacific the predominant class of phytoplankton is diatoms, which are associated with high trophic transfer [43]. Many species (including the dominants: *Skeletonema costatum*, *Thalassiosira* spp., and *Chaetoceros* spp.) occur along the entire coast of BC [44–50]. Large blooms associated with coastal upwelling are often monospecific (*e.g.* [51]), but in our region they appear to be more diverse and occasionally include large numbers of photosynthetic dinoflagellates [46, 52]. Coccolithophorid blooms have been directly observed in

Table 1. Terminology used in the text to quantify levels of P_{CO2} used in manipulation experiments. S2 Table provides details for each treatment in each experiment cited.

Terminology	P_{CO2}
present-day	depends on depth range (Fig. 2)
reduced	0.5x present-day
elevated	2–5x present-day
very elevated	5–10× present-day

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more protected regions [50] and by satellite along the entire BC coast during summer [53]; however, coccolithophores (which calcify) are generally assumed to contribute minimally to overall productivity in the coastal zone (roughly landward of the 800 m isobath, Fig. 1) despite their importance further offshore [54]. Primary production by phytoplankton is exceptionally high in the region [27, 47, 55] and ultimately responsible for the high fish yields along our coast [30].

Phytoplankton species that are harmful to higher trophic levels are also common in the region. Large blooms of diatoms from the genus *Pseudo-nitzschia* occur on the outer coast (*e.g.* [56, 57]) while the dinoflagellate *Alexandrium* is more prolific in protected locations [58]. Both *Pseudo-nitzschia* and *Alexandrium* produce neurotoxins that bioaccumulate in higher trophic levels. These toxins can interfere with the reproductive success of fish, seabirds, and mammals and cause mass mortalities [59, 60]. They are also responsible for numerous seasonal shellfish closures in BC (http://www.pac.dfo-mpo.gc.ca/fm-gp/contamination/biotox/index-eng.html). Additionally, significant blooms of *Heterosigma akashiwo* occur in protected waterways [61, 62]. *Heterosigma* releases peroxide free radicals into the water [63], which damage fish gill tissue [64, 65] and cause significant mortality and monetary losses (millions of dollars per year) to salmon aquaculture in BC [66]. Thus, harmful algae already pose a threat to health and food safety along the BC coast [58].

Direct effects There have been numerous studies on phytoplankton related to OA (S1 Table) and a variety of responses have been observed depending on the species and the experimental treatment (*e.g.* [67–70]). Although natural conditions in most coastal environments, including the BC coast (Figs. 1 & 2), cover an exceptionally large range in carbon states and consequently pH (*e.g.* [6, 27, 71]), experiments in the field are challenging to complete. Thus, most studies have been conducted in the laboratory, often using a single strain of cultured phytoplankton. Also, because coccolithophores calcify (and at least some are easy to culture), they have been studied disproportionately. We sample a relatively small subset of this body of literature to summarise results of most relevance to the mixed, often diatom-dominated, community in the region and briefly describe the current understanding of the mechanisms involved.

Species specific responses by primary producers, including phytoplankton, to increases in ambient CO_2 are highly dependent on their carbon-uptake mechanism. Carbon assimilation relies on the enzyme ribulose biphosphate carboxylase-oxygenase (RuBisCO) to fix CO_2 [72], but this enzyme has a poor affinity for CO_2 [72, 73]. Over geological times scales (i.e. the last 3.5 billions years), as newer phytoplankton species have evolved, their use of RuBisCO has become more effective [72]. Some have carbon-concentrating mechanisms (CCMs), *e.g.* diatoms [74], to help transport and accumulate CO_2 to the active RuBisCO site [75]. The most important CCM for phytoplankton involves carbonic anhydrase to convert abundant HCO_3^- to the limiting CO_2 [76]. Despite CCMs, many photosynthetic phytoplankters, including some diatoms, appear to be carbon-limited under present-day conditions (*e.g.* [72]).

Because of these limitations in carbon uptake, it is anticipated that OA will increase overall production, which may provide more food to higher trophic levels. However, this increase does not appear to be large. Numerous mesocosm experiments, which use natural assemblages, suggest that regardless of species composition, there may be at most a 10–30% increase in primary production due to OA (*e.g.* [77–80]). In addition, a side-effect of elevated P_{CO2} (Table 1) is increased carbon to nitrogen (C:N) ratios in phytoplankton, effectively decreasing its nutritional quality [80].

While it is generally agreed that OA is likely to cause shifts in phytoplankton species composition, it remains unclear what these shifts will be [69]. It is reasonable to expect that species that do not have effective CCMs will do better than species that are already efficient with carbon uptake (diatoms in general). For example, the fish-killing raphidophyte *Heterosigma akashiwo* relies on passive diffusion to obtain CO_2. As a result it responds strongly (increased rates of growth and primary productivity) to an increase in dissolved CO_2 [81, 82] regardless of temperature [82]. In contrast, growth rates for some phytoplankton species reach a maximum value at the low end of present-day P_{CO2} in the upper mixed layer on the outer BC coast (Fig. 2) assuming a salinity of 31–32 [81]. For other species (including several diatoms) these rates remain invariant under elevated P_{CO2} [83].

Competition may be more subtle. For instance, some experiments have shown an increase in the proportion of diatoms relative to smaller phytoplankton with increased P_{CO2} (*e.g.* [84]) while others show the opposite effect (*e.g.* [85]). In addition, Tortell *et al.* [86] found that the prymnesiophyte *Phaeocystis* could outcompete diatoms at reduced P_{CO2} even though both groups have efficient CCMs. Finally, it has been suggested that at least one motile species (*H. akashiwo*) will swim faster under OA and deepen its vertical distribution [87], which may give it (and any species that can take advantage of its absence nearer to the surface) an additional competitive advantage.

Factors associated with climate change, including OA, are expected to increase the frequency and severity of harmful algal blooms [88]. In addition, the production of potent neurotoxins —domoic acid by common and sometimes prolific diatom species of *Pseudo-nitzschia*, and saxitoxin by dinoflagellate species of *Alexandrium*—has been shown to increase markedly under OA conditions [89–91]. In fact, domoic acid production in (at least some) *Pseudo-nitzschia* spp. increases dramatically (5–50× per cell) as P_{CO2} increases [92, 93].

Coccolithophores (prymnesiophytes) are the major calcifiers in the phytoplankton community [94, 95]. The most commonly studied species is *Emiliania huxleyi*, and although it appears to be less prevalent locally in the coastal zone (Fig. 1 in [94]), it plays an important role in the Alaskan Gyre [54]. Numerous experiments (most *in vitro*, some *in situ*) on *Emiliania* have been conducted to determine the effects of carbonate chemistry on calcification. Most (but not all, *e.g.* [96, 97]) suggest decreasing calcification at lower pH values (*e.g.* [70, 98]). Although much remains unknown (*e.g.* [20, 99]), the consensus is that OA will decrease calcification [69]. This observation is reinforced by mesocosm experiments that manipulate coccolithophore populations [67, 100] and by paleolithic records [101].

Phytoplankton synopsis We conclude that the overall impact on ecosystems and fisheries due to changes in the phytoplankton community in our region will be negative. While a modest increase in primary production is anticipated (so a direct positive benefit to phytoplankton, Fig. 4A), this increase is not likely to benefit higher trophic levels due to expected shifts in species composition (away from diatoms) and decreased nutritional value of the plankton. More importantly, the fish-killing alga *Heterosigma akashiwo* may gain a competitive advantage, which would seriously threaten salmon aquaculture. In addition, increasing P_{CO2} has been shown to alter the mix of neurotoxins produced by genera such as *Pseudo-nitzschia* and *Alexandrium* to favour the more potent forms, posing a significant threat to higher trophic levels and the shellfish industry as well as overall food safety.

Macroalgae

Three groups of macroalgae are delineated by their pigmentation: green, brown, and red algae, all of which are common in BC. In particular, brown algae constitute the majority of the biomass in intertidal and upper subtidal zones, and are dominated by kelps and rockweeds [102]. Brown algae have soft fleshy morphologies, and both green and red algal groups contain species with hard, calcified structures. Calcified red algae have two morphologies, crust-forming on substrate, and erect and branched. Both red and green algae are found in the intertidal and upper subtidal zones, but red algae extend down to the lower photic zone [103]. The large-blade (brown) macroalgae (*e.g. Laminaria, Macrocystis*) that form dense kelp forests along temperate coasts, common in BC, are the basis of some of the most productive ecosystems on Earth [103, 104]. These forests provide extensive shelter from predation, desiccation and wave action, as well as food, for hundreds of species with representatives from most taxonomic groups [105]. Calcified red algae provide similar protective structures, that are especially important for invertebrate species (*e.g.* urchins and anemones) [106].

Direct effects As with phytoplankton, many macroalgal species use carbon concentrating mechanisms (CCMs) to help transport and accumulate the CO_2 required for carbon assimilation [107]. Those relatively rare species without CCMs (most of which are red algae) rely on passive diffusion of CO_2 [108, 109] and so may experience enhanced photosynthesis and growth under OA, whereas those that have CCMs are likely to show no, or only small, positive effects due to reduced energy expenditure [107, 110]. Responses to elevated P_{CO2} (Table 1) may be more significant at depths where light levels are reduced because energy constrains photosynthesis and CCMs are energetically expensive, though these effects are likely to be species-specific [110]. In addition, UVB (Ultraviolet B, 280–315 nm) exposure near the water surface tends to be harmful to some macroalgae, reducing the positive response to elevated P_{CO2} [111]. The ultimate effects of OA on photosynthesis and growth of macroalgae will likely depend on interactions with light exposure, UV radiation, and other stressors. There has been less research concerning reproduction and life stages; however, it has been suggested that OA will result in reduced gametophyte growth of giant kelp [112].

For calcifying macroalgae, elevated P_{CO2} affects the ability to build and maintain the calcified component of their tissues [108]. For example, Hofmann *et al.* [113] observed reduced calcification and growth for a cosmopolitan species of red algae when exposed to elevated P_{CO2} over a 4-week period (S2 Table). Calcifying red algae are particularly sensitive to OA because unlike most calcifying green algae and invertebrates, red algae deposit a high-magnesium form of calcite into their cell walls, that is more soluble in acidified water than other forms of calcite [28]. However, Kroeker *et al.* [36] found no consistent change in calcification at elevated P_{CO2} levels for a suite of calcifying macroalgae, perhaps because many species are able to generate microenvironments suitable for calcification despite increases in ambient P_{CO2} [114–117]. Indeed, the observed reductions in growth with elevated P_{CO2} (*e.g.* [113]) may result from the increased dissolution of carbonate skeletons rather than reduced production [117]. These effects are likely to interact with other stressors, such as UV radiation and temperature [118]. For example, Gao and Zheng [119] suggest that the carbonate skeleton of the same red algal species serves as a protective layer against UV; thus, CO_2 induced shell dissolution may increase vulnerability to detrimental effects of UV radiation [119].

Indirect effects Changes in macroalgal community composition are anticipated given the diversity of responses to OA among species. In general, non-calcifying macroalgae (especially those that rely on diffusion of CO_2 instead of CCMs) are expected to experience increased competitive success compared with calcifying macroalgae [110], resulting in an overall shift of community composition toward non-calcifying species [36]. Furthermore, studies on CO_2-enriched waters surrounding seafloor vents elsewhere support this hypothesis [120]. Most research has focused on losses of crust-forming calcified red algae in particular and replacement with non-calcifying turf-forming algal communities (*i.e.* species that reach heights of <15cm [121]) [36, 115, 122]. In BC, crust-forming red algae release chemical cues that play an important role in the settlement of some invertebrate larvae (*e.g.* abalone [123, 124]), and they bond substrata to provide stable habitats for other benthic species [106], but the resulting ecosystem effects under OA remain highly uncertain. Likewise, the ecological effects of possible declines in erect calcified red macroalgae and replacement by fleshy macroalgal species have received little attention (but see [113, 125]).

In addition to competition, herbivory is another key factor structuring macroalgal communities [126]. Rates of herbivory on macroalgae depend on palatability and the presence of hard carbonate structures for algal defence [127]. OA may reduce structural protection thereby increasing grazing on calcified species [115]. For non-calcified species, OA may increase C:N ratios possibly reducing palatability and hence grazing pressure [115]. However, OA will likely be detrimental to many herbivores, especially calcified species such as echinoderms and molluscs (see below), with resulting beneficial effects on some macroalgal species (*e.g.* [128], Mediterranean Sea, S3 Table).

Given these potential impacts, Harley *et al.* [115] suggest that in the California Current ecosystem, which includes the WCVI, OA may result in a shift from diverse nearshore communities consisting of kelp canopies, understory turf assemblages, crust-forming calcifying algae, and calcifying invertebrates (*e.g.* urchins), to communities dominated by kelp and macroalgal turfs. Where kelp canopies have been lost due to other natural or anthropogenic disturbances (*e.g.* indirect effects of commercial harvest of fish species as found for large regions of the northeast Pacific, [129]), OA may prevent kelp recovery by facilitating expansion of algal turfs which inhibit kelp recruitment [130], as found along the Australian coast [131]. Kelp is the dominant primary producer among macroalgal species in BC, providing food and habitat for commercially important fish species, such as Pacific salmon [132, 133]. However, because responses of benthic communities to OA are highly species-dependent, the results of these studies cannot be extrapolated to other regions with high confidence [115].

In addition to community-level effects from altered competition and herbivory, OA may slow decay rates of some kelp species including those commonly found in BC (*e.g.* bull kelp, *Nereocystis leutkeana*), which could indirectly affect detritivore consumption and nutrient cycling [111]. This delay may result in the accumulation of phytodetritus, possibly reducing food availability for consumers in nearshore waters.

Macroalgae synopsis The direct effect of OA is hypothesised to be positive on non-calcifying species due to enhanced availability of CO_2 for carbon assimilation, but negative for calcifying species due to reduced growth and dissolution of protective shells (Fig. 4A). Community composition may shift from calcifying macroalgae species toward non-calcifying species, with an inhibition in the recovery of depleted kelp populations. However, community-level responses will depend on the extent of grazing on fleshy, non-calcifying species, possible changes in grazing due to OA-impacts on invertebrate herbivores, and the expansion of algal turfs. Responses of benthic communities to OA are highly species-dependent, limiting confidence in generalisations and extrapolations among regions and studies.

Seagrasses

Seagrasses belong to a small group of marine angiosperms comprising 60 species worldwide [134]. In BC, there are only two species of eelgrass—the native *Zostera marina* and the introduced species *Z. japonica*—and three species of surfgrass all belonging to the genus *Phyllospadix* [135]. Seagrass beds are well-known as nurseries for juvenile fish and invertebrates [136]. Another advantage conferred by seagrass beds is their ability to modify the seawater carbonate system, increasing aragonite saturation states within their confines [137], which might offer calcifying organisms refugia from the effects of OA.

In contrast to most macroalgae, seagrass cannot take advantage of the abundant HCO_3^- [138] and so increase their photosynthetic rate when DIC becomes more abundant [139]. With more DIC, seagrass are better able to compensate for light attenuation [139]. As a result, increased P_{CO2} may foster the growth of seagrass beds, despite worldwide losses of seagrass ecosystems due to anthropogenic disturbances along coastal environments [134]. However, OA-related reductions in phenolic compounds [140], which protect seagrasses against herbivory, may result in increased grazing pressure under increased P_{CO2}. The evidence for decreasing phenolics in seagrass under OA is limited and contrary to the trend of increasing phenolics in terrestrial angiosperms under increased atmospheric CO_2 [140].

Seagrass synopsis Seagrasses will likely benefit from increased P_{CO2} because higher DIC helps them compensate for light limitation; however, a decrease in protective phenolic compounds may offset any benefit due to increased grazing. The net effect of increased OA will likely be neutral for seagrasses.

Microzooplankton

Microzooplankton (20–200 μm) include heterotrophic protists such as ciliates and non-photosynthetic dinoflagellates. Typical ciliate genera along the BC coast include *Strombidium*, *Tintinnopsis* and *Strobilidium* [141] while the heterotrophic dinoflagellate species belong chiefly to *Protoperidinium*, which feeds almost exclusively on diatoms [142], and *Gyrodinium*. In near-shore waters, microzooplankton can be very abundant, depending on the time of year and food source (*e.g.* [44]). More importantly, fluctuations in microzooplankton populations, tightly coupled to phytoplankton, can have a large effect on pelagic ecosystems [143] and can influence the success or failure of fish recruitment [144].

Direct effects There are no studies that test the direct effects of OA on individual microzooplankton species. That said, foraminifera are amoeboid protists that form $CaCO_3$ shells and, like coccolithophores, are probably at risk from OA (*e.g.* [145]). There is also speculation that microzooplankton motility might be affected by OA [146], with the closest evidence coming from the study of the photosynthetic flagellate *Heterosigma* that demonstrated an increase in swimming speed and an increase in downward migration [87]. Large-scale mesocosm manipulations and on-board experiments that compare present-day and elevated P_{CO2} (Table 1) have found conflicting results—(i) no shifts in composition or abundance [147–149], (ii) almost identical succession patterns [150], and (iii) significant increases in heterotrophic dinoflagellate abundance [151, 152], although in the former (i.e. [151]) an increase in the prey species of diatoms was likely responsible.

Microzooplankton synopsis Based on the limited studies for microzooplankton, we expect that most species will be unaffected by OA, except through changes to their prey (phytoplankton). Direct OA effects will likely have a negative effect on foraminifera through reductions in $CaCO_3$ shells.

Mesozooplankton

In our region, the zooplankton community is strongly dominated by calanoid copepods [153, 154]. Important species include *Neocalanus plumchrus*, *Acartia longiremis* and *Pseudocalanus* spp. [153, 154]. In protected regions like the Strait of Georgia (Fig. 1) *Calanus pacificus* is also important [154], while on the outer shelf *Calanus marshalae* is significant [153]. Some species spend part of their life cycles (that includes egg production) in relatively deep waters, >300–500 m (*e.g. Neocalanus plumchrus* and *Calanus pacificus*) while others, like *Acartia longiremis*, are always found above ~50 m. Zooplankton productivity is variable and appears to be changing over time [153], with species composition dependent on temperature [154]. Mesozooplankton provide the main trophic link connecting phytoplankton and microzooplankton with larger oceanic predators [155]. They are critical for several commercially-valuable fish species that prey on them directly, such as Pacific Herring, Pacific Hake, Pacific Sardine, various salmon species, and Spiny Dogfish (*Squalus acanthias*) [155].

Direct effects Only *Calanus pacificus* has been studied locally so we include experiments on copepods found elsewhere from the common genera *Acartia* and *Calanus*. Although responses to acidic conditions can be species-specific, even within genera (*e.g.* [156]), our summary provides a general indication of possible effects on the mesozooplankton community in our region.

Most OA related mesozooplankton research involves eggs and/or survival rates within individual stages. Egg production rates of adult females appear unaffected by increased P_{CO_2} (eveu under very elevated conditions, Table 1) [156–160], although P_{CO_2}-induced increases or decreases were observed depending on temperature [161]. On the other hand, egg hatching rates may decrease with OA [156–160], although increases have also been observed [161]. However, it is possible that hatching is simply *delayed* and so not observed in short-term experiments [160]. Effects of OA on overall egg hatching success are uncertain. In Puget Sound, WA (Fig. 1), egg hatching in *Calanus pacificus* is reduced under elevated P_{CO_2} (Anna McLaskey, pers. comm., University of Alaska, Fairbanks AK), whereas egg hatching success in *Calanus helgolandicus* (found in the North Atlantic) appears unaffected [162]. For copepod embryos, survival rates appear unaffected by OA, while developmental rates may decline [163]. In adult copepods, survival rates are not significantly affected even under very elevated experimental conditions (except for one species) [156, 157, 159].

Although impacts on individual life stages may not be significantly different from a control scenario, the cumulative impacts may be significant. In addition, the studies thus far have been relatively short-term, and do not consider the possibility for copepods to respond to environmental changes through adaptive evolution [161]. The lack of detailed information on potential effects on zooplankton physiology "currently restricts our ability to reliably predict future impacts" [162].

Mesozooplankton synopsis For copepod species from the genera *Acartia* and *Calanus*, adult survival rates and egg prodnctions rates appear unaffected by OA, even when P_{CO_2} is 'very elevated' (Table 1), whereas egg hatching rates are negatively affected and egg hatching success remains uncertain. Cumulative impacts across life stages are unknown. Thus, the effects of OA on mesozooplankton will likely be neutral and possibly negative (Fig. 4A).

Pteropods

In BC waters only three species of pelagic snail, or pteropod, have been regularly observed [164]. *Limacina helicina* (shelled) is by far the most common of these three, occurring throughout most of the year, generally in the upper 100 m [164] and occasionally forming strong blooms (> 1000 m^{-3}) which can dominate the plankton (M. Galbraith, pers. comm., Institute of Ocean Sciences, Sidney BC). *Clione* spp. (naked) is also often present, although at significantly lower numbers. These two species are common in the Strait of Georgia and less so in Hecate Strait (Fig. 1); they are also found on the outer BC shelf and in the Alaskan Gyre (M. Galbraith, pers. comm.). *Clio pyramidata* (shelled), a subtropical species, is present only episodically along the WCVI [165]. Pteropods are an important food source for fish (especially juvenile salmon [166]), birds and marine mammals [167, 168]. Most pteropods produce aragonitic shells [167] and those that don't (naked pteropods) feed almost exclusively on the shelled species, making all pteropods susceptible to OA [164].

Direct effects It is difficult to keep pteropods in laboratory conditions [164] due to their delicate feeding structure [167]. Thus, few controlled experiments on live animals have been made until recently, and sample size remains limited. Most of these experiments have been conducted on (variants of) *L. helicina* harvested from Arctic and Antarctic waters (S2 Table).

Shells of dead pteropods dissolve in waters undersaturated with respect to aragonite, (*e.g.* [169, 170]) as expected. Live individuals, which may form protective biological coatings on the exterior of their shell [171] and/or actively counteract dissolution [170] also show evidence of dissolution when harvested from waters under, or near, saturation with respect to aragonite [172–174] (S3 Table). Similarly, live individuals incubated for short periods under the high end of present-day P_{CO_2} (0–100 m, Fig. 2) and elevated P_{CO_2} (Table 1) show reduced calcification (*e.g.* [170, 175]; S2 Table). In one experiment the larval state failed to calcify at all [176].

Despite the negative impacts on shell quality and maintenance, many (and in some cases all, *e.g.* [175]) animals studied survived their respective treatments (*e.g.* [170, 177]). However, the reduction of shell formation will impact the pteropods' ability to control buoyancy and withstand predation [167]. In addition, as P_{CO_2} rises, increased energetic costs associated with maintaining their shells are likely, particularly as temperature increases [170]. The ability to supply energy to perform these (and other) tasks may be suppressed, [178] although some pteropods are likely to be more resilient than others (*e.g.* [179], S2 Table).

Pteropod synopsis In summary, there is a clear cause for concern about the future of pteropods and the animals that depend on them. Although in the last several decades pteropods make up, on average, only about 5% of the average annual zooplankton biomass in BC waters (M. Galbraith, pers. comm.), they are an important food source for juvenile Pink Salmon [166] and are related to Pink Salmon survival [180] (see Fish—Indirect effects). Already in our region, where aragonite saturation horizons are frequently shallower than 100 m [11, 31, 32], numbers of the most common pteropod have declined significantly [164].

Molluscs

Molluscs comprise a diverse group of organisms that includes a variety of shellfish as well as predators such as squid and octopus (and pteropods, above). In the northeast Pacific, mussels dominate rocky intertidal zones (*e.g. Mytilus californianus* [181]) while oysters (mainly the Pacific Oyster, *Crassostrea gigas*), clams (family Veneridae) and cockles (family Cardiidae) are commonly found on beaches [182]. Geoduck Clams and scallops live significantly deeper (~10–20 m and 15–45 m, respectively) as do squids and octopuses (~15–140 m, Fig. 3). Shellfish consume plankton through filter-feeding and are able to significantly reduce plankton concentrations on a local scale (*e.g.* [183]), making them strong indicators of water quality [184, 185]. In turn, shellfish are preyed upon by many animals including sea otters, octopuses, seabirds and sea stars [186, 187].

The annual landed value of molluscs harvested from wild and farmed fisheries in BC is $63 million (Fig. 4), of which 66% is Geoduck Clam (*Panopea abrupta*). Other major harvested clams are Manila Clam (*Venerupis philippinarum*), Native Littleneck Clam (*Leukoma staminea*), Butter Clam (*Saxidomus gigantea*) and Varnish (Savoury) Clam (*Nutallia obscurata*) [188]. The Pacific Oyster was introduced into BC waters in the early 1900s and is used in aquaculture, while the native Olympia Oyster (*Ostrea conchaphila*) is no longer harvested [189, 190] and is listed as *Special Concern* under the Canadian Species at Risk Act (SARA). There are small fisheries for Pink Scallop (*Chlamys rubida*) and Spiny Scallop (*Chlamys hastata*) [191]; a commercially-developed hybrid called "Pacific Scallop" (*Patinopecten caurinus x yessoensis*) is used in aquaculture. There is a small but growing mussel industry, no harvest for Northern Abalone (*Haliotis kamtschatkana*) as it is listed by SARA as *Endangered*, and minor harvests for squid and octopus.

Direct effects Shelled molluscs calcify internally and actively increase pH at that site to do so, making them directly vulnerable to OA [16, 17]. Larval shells are particularly vulnerable since they are mostly composed of aragonite [192, 193] and for at least a few species the initial deposit is amorphous $CaCO_3$ (the least stable form of $CaCO_3$) [192]. By adulthood, shells are composed of aragonite and/or calcite, depending on the species [192, 193]; *e.g.*, oyster shells are mainly calcite [194]. To deal with vulnerability at the larval stage (*e.g.* [195]), mollusc aquaculture in the northeast Pacific relies on hatcheries (often with controlled conditions) to rear larvae that are then distributed to growers.

Experiments to quantify OA effects on shellfish have yielded a range of conclusions [36, 196]; however, with the advancement of the field, results are beginning to converge. Kroeker et al. [36] found that OA significantly reduced calcification (by 40%), growth (by 17%) and development (by 25%) in molluscs. Another recent review [197] found that 37 of 41 studies on calcification by molluscs reported significant negative effects following exposure to increased CO_2 levels. Here we summarise experiments performed on species that are found in the northeast Pacific and elsewhere (*e.g.* scallops). There have been no studies on Geoduck Clams (despite their commercial importance), or on BC scallop species.

Experiments on fertilisation in Pacific Oyster have produced mixed results. Both sperm swimming speed and egg fertilisation success can be unaffected [198] or decline [199, 200] under elevated P_{CO2} (Table 1). Within two days of fertilisation, Pacific Oyster larvae precipitate >90% of their body weight as $CaCO_3$, using limited energy reserves in eggs [17]. Early development (up to 8 h) remains unaffected at elevated P_{CO2} [201]; however, the number of embryos reaching the planktonic 'D-veliger' larval stage declines [199–201]. Elevated P_{CO2} increases the number of larvae with shells one day after fertilisation (due to an enhanced metabolic rate), yet decreases it three days after [202]. Larval survival of Pacific Oysters is unaffected by P_{CO2} after three and 16 days [202, 203]. Species that do exhibit a decline in larval survival are Northern Abalone [204] and Bay Scallop (*Argopecten irradians*) [205].

Metamorphosis from larvae to juveniles is affected differently for different species under elevated P_{CO2}. For Olympia Oyster, the proportion of metamorphosing larvae declines [206, 207] and size at metamorphosis decreases [206]. Similar results, plus a delay in metamorphosis and reduction in survival, are usually seen for Bay Scallop [205, 208–210]. However, for Northern Abalone from the WCVI the proportion of metamorphosing larvae is unaffected [204]. Increased abnormalities in larvae have been observed under elevated P_{CO2} in Pacific Oyster [199–201] and Northern Abalone [204]. In the latter species, shell abnormalities increased substantially, occurring in 99% of larvae at P_{CO2} 1800 μatm [204]. These abnormalities did not appear to affect survival rates in the laboratory, but in the field the abnormal larvae would be more susceptible to predation [204].

The size of D-veliger larvae of Pacific Oyster decreases [199–202, 211] and shell growth of later larval stages generally declines [199, 201] under elevated P_{CO2}, though not always [199, 203]. Decreases in larvae shell growth also occur in Olympia Oyster [207, 212], Northern Abalone [204] and Bay Scallop [208–210]. Molecular analyses show that expression of proteins related to calcification and cytoskeleton production can be severely suppressed under high P_{CO2} [211]. For Northern Abalone larvae, settlement (attachment to the experimental container) is unaffected by P_{CO2} [204]. Additional effects on other larvae include decreased O_2 consumption and feeding rates [203], and reduced lipid content [209, 210].

Shell growth and calcification of juvenile and adult molluscs under OA remains uncertain due to limited studies with contrasting results. Pacific Oyster juveniles exhibit increased expansion of shell area (but not thickness) under reduced pH, despite declines in O_2 consumption and feeding rates of larvae [203]. In juvenile Bay Scallops, elevated P_{CO2} (Table 1) does not affect shell and tissue growth but does reduce survival [209]. Declines in calcification rates have been observed for Pacific Oyster juveniles and adults under elevated P_{CO_2} [213] and for adult Zhikong Scallops (*Chlamys farreri*) under reduced pH [214].

The byssal threads that mussels use to attach themselves to rocks or vertical lines in aquaculture must be robust so that they do not drop off or get ripped off. The threads of the common mussel (*Mytilus trossulus*) have been shown to weaken under elevated P_{CO_2} [215], although they may be more sensitive to temperature during during short-term fluctuations typical of local inlets (L. Newcomb, University of Washington, Seattle pers. comm.).

Metabolic rates of juveniles and adults appear to be generally unaffected by OA alone [216–218]. Also unaffected, at least in juvenile King Scallops, are clearance rates, growth rates, the ratio RNA:DNA (suggesting no effect on growth potential) [217], and various measures related to 'clapping' (rapid closing used for locomotion) by adults—frequency, recovery time between claps and clapping fatigue [218]. The latter study, however, did find a reduction in the force exerted by the clapping under elevated P_{CO_2}, which could reduce the scallops' ability to escape predators.

As above, the larval stage is vulnerable to OA. South of BC, at a hatchery for Pacific Oyster in Oregon (USA), carbonate levels experience large fluctuations due to strong coastal upwelling [195]. Negative correlations were found between the aragonite saturation state (Ω_{arag} of water in which larvae were spawned and reared, and the resulting larval production and mid-stage growth [195]. In the laboratory, the shell growth rate of juvenile Olympia Oysters depends on pH exposure at the larval stage but not at the juvenile stage [212]. To test such carry-over effects in a natural system, Olympia Oyster larvae were reared under different P_{CO_2} levels, then transferred to field sites after metamorphosis [206]. Juvenile survival was not significantly different between the two larval treatments, but the elevated-P_{CO_2} larvae yielded smaller juveniles, suggesting that they suffer irreversible damage (*e.g.* energy deficit, abnormality, inability for compensatory growth) [206].

Indirect effects Changes in species composition can be expected under OA. Few studies explore these changes for molluscs, however it has been shown that Eastern Oyster larvae (*Crassostrea virginica*) have higher survival rates than Bay Scallops under elevated P_{CO_2}, which is the opposite of the present-day P_{CO_2} result (and in the absence of brown tides—in this study caused by a temperate phytoplankton species not found in the northeast Pacific) [210]. Thus, scallops may be affected by OA more than oysters. Scallops are also sensitive to other anthropogenic stressors, such as eutrophication [219], while the impact of these conditions on oysters and other shellfish was not investigated.

OA may increase the vulnerability of shelled molluscs to predation by thinning their protective shells and may also cause food web shifts. For example, Boring Sponges (*Cliona celata*) can bore twice the number of holes in Bay Scallop shells, and remove twice the weight of shell, at pH 7.8 compared to pH 8.1, despite taking longer to attach themselves to the shells [220]. Negative impacts on molluscs could also have large unintended consequences for other species [221]. Shell production and aggregation provide refuge for other organisms such as sponges and crabs, and introduce complexity and heterogeneity into benthic environments, with heterogeneity being important for maintaining species richness [221]. Thus, the direct effects of OA on molluscs may have detrimental effects at the ecosystem level.

Squid and octopus In BC, there are at least 30 species of squid and eight species of octopus [222], none of which have been studied for OA effects. Common species in BC waters are Opal Squid (*Loligo opalescens*) and Northern Giant Pacific Octopus (*Enteroctopus dofleini*). Similar to the otoliths of fish (see below), squids have internal calcified structures called statoliths used for sensing gravity and movement [223]. Under elevated P_{CO_2} statoliths in embryos of the European Squid, *Loligo vulgaris*, are significantly larger than those formed under present-day P_{CO_2} [224]. At higher P_{CO_2} (still in the elevated range—Table 1), Kaplan *et al.* [225] observed reduced surface area, malformation, and abnormal crystalline structure in statoliths of Atlantic Longfin Squid, *Doryteuthis pealeii*. Aside from calcification, elevated P_{CO2} also leads to increased heavy metal retention in the protective eggshells and changes to the bioaccumulation of silver, mercury and cobalt in larval tissue [224]. Additionally, elevated P_{CO2} depresses metabolic rates in pelagic squids (*e.g.* [226]). The ultimate effect on fitness is not known.

Mollusc synopsis We conclude that the effects of OA on shelled molluscs will be negative based on available studies on oysters, scallops, abalone and mussels (Fig. 4). These negative effects occur at various life-history stages, and go beyond direct effects on calcification of larvae, *e.g.* reduced oxygen consumption and feeding rates of larvae and delayed behavioural responses of adults. It is generally anticipated that effects on larval survival rate and reproduction rate will directly influence population size, population distribution and community structure [227]. No experiments were found on local clam species (including geoducks) but given the results on other molluscs [36] we anticipate that they will also be negatively affected by OA, while effects on squid and octopus remain uncertain (Fig. 4).

Sponges and Coldwater Corals

Sponge reefs are globally unique to the northeast Pacific coast [228–230] and all four groups of cold-water corals: octocorals, stylasterids, stony and black corals, are present in the region. They occur where productivity and water flow are high (*e.g.* they are especially dense on seamounts and the heads of canyons, Fig. 1) and from the surface to depths >2000 m [231]. However, due in part to the depth range, very few benthic habitat mapping data exist along the BC coast (*e.g.* [232], Kim Conway, pers. comm., Pacific Geoscience Centre, Sidney, BC) and so we have used these data and the expertise of others to provide our own general description (below). Sponges and cold-water corals form important habitat for many marine organisms including species of fish that are commercially important (*e.g.* the rockfish Pacific Ocean Perch) in our region [233–236].

The coral and sponge contribution to the benthic fauna in BC appears to be patchy but diverse, based on: DFO trawl survey and observer records [237], comparison with neighbouring regions (*e.g.* [238, 239]), isolated studies (*e.g.* [229, 235]), anecdotal evidence (Lynne Yamanaka, pers. comm., Pacific Biological Station, Nanaimo, BC), and modelling work (*e.g.* [240]). This collection is likely dominated by siliceous sponges, and isolated stands of flexible corals with partly organic skeletons (octocorals), more specifically members of the diverse group Alcyonacea (*e.g.* large tree form coral) and pennatulaceans (sea pens and whips). Alcyonacea and solitary glass sponges occur on bedrock, mainly deeper than ~200 m, while pennatulaceans and glass sponge reefs grow on flat sediment, generally shallower than ~200 m [241].

Stylasterids (*e.g.* [242]) and stony corals (Scleractinia) also occur [237, 243], but primarily in small, solitary patches. The reef-forming scleractinian *Lophelia pertusa* has been found [244], but is rare, possibly influenced by the already low aragonite saturation states in this region [245]. Black corals, which do not calcify and are made of organic proteins, are also present below 500 m [237].

Direct effects OA studies have focused on stony corals, primarily *Lophelia pertusa*, which is entirely aragonitic. They show an increased energetic cost for calcification in *L. pertusa* with decreasing pH (and Ω_{arag} [246, 247] (S2 Table); however, *L. pertusa* may adapt to moderate decreases in pH given sufficient time [248] (S2 Table). The holdfasts and some parts of the structure of many octocorals are also made of aragonite [249]. Similarly, some stylasterids precipitate aragonite as well as calcite [250]. However, neither octocorals nor stylasterids have been studied with respect to OA to date. Likewise, there are no OA studies specific to glass sponges.

Sponge and coral synopsis The OA response of the cold-water corals most common in our region (octocorals) has not yet been studied. While the skeletons of these corals are partly organic, they also calcify and so may be affected by OA at some level (Fig. 4A). There are no OA studies on glass sponges to date. Loss of coral and sponge habitat would have a negative impact on many fish species, particularly juvenile rockfish [233–235].

Echinoderms

Echinoderms form a marine set of invertebrate animals with ~7000 known species worldwide [251] and 217 species recorded in BC [252], half of which occur exclusively at depths > 200 m [253]. The echinoderms comprise five classes: (i) echinoids (sea urchins and sand dollars), (ii) asteroids (sea stars), (iii) holothuroids (sea cucumbers), (iv) crinoids (sea lilies and feather stars), and (v) ophiuroids (brittle stars). A few are considered to be "keystone" species, such as the Purple Sea Star (*Pisaster ochraceus*) [254, 255], which is common along the BC coast. Echinoderms modify ecosystems (*e.g.* by mixing and transforming sediments, grazing kelp forests, preying on mussel beds) and provide food for carnivorous fish, shellfish, and marine mammals (*e.g.* sea otters prey heavily on sea urchins and sea cucumbers). In addition, sea stars and sea urchins act as important grazers in the sub-littoral zone [256].

Direct effects Green and Red Sea Urchins (*Strongylocentrotus droebachiensis* and *S. franciscanus*, respectively) harvested in BC generate significant income (Fig. 4A). Clark *et al.* [257] found that larval growth and skeletal calcification were reduced at lower pH levels for select species (see S2 Table) ranging from the tropics to the poles; no changes in skeletal morphology occurred. Studies on shell thickness are confounded by effects of diet and experiment length [125, 258], but urchins have higher growth rates when fed on calcifying algae and may derive some portion of essential elements (*e.g.* calcium, magnesium) from the algae [258]. Therefore, sea urchins may suffer as the proportion of calcifying macroalgae in their diet declines due to direct OA effects on these algae (see Macroalgae section above). In long-term studies, sea urchins have shown an ability to adapt to elevated P_{CO_2} (Table 1); however, in the transition to new OA conditions, species may suffer from life-cycle carry-over effects. For instance, Dupont *et al.* [259] demonstrated that under elevated P_{CO_2} females acclimated for four months experienced a 4.5 decrease in fecundity and produced offspring that suffered 95% juvenile mortality; however, these effects disappeared after acclimitisation for 16 months (S2 Table). OA may also influence reproduction in echinoderms. For example, as P_{CO_2} increases under OA, higher sperm concentrations are necessary to achieve high fertilisation success in the sea urchin *S. franciscanus*, and the egg's mechanism for blocking fertilisation by multiple sperm cells becomes slower [260].

A number of studies have used genetic markers to infer the possible physiological effects of OA in sea urchins (see S2 Table). O'Donnell *et al.* [261] measured the change in expression of a molecular helper-protein in *S. franciscanus* and suggested that the ability to handle temperature stress would be reduced under OA. Todgham and Hofmann [262] measured changes in ~1000 genes of the sea star *S. purpuratus* and found reduced expression under elevated P_{CO_2} in four categories—biomineralisation, cellular stress response, metabolism, and apoptosis (cell death). Also for this species, elevated P_{CO_2} triggered changes in 40 functional classes of proteins, affecting biomineralisation, lipid metabolism, and ion homeostasis [263].

Giant Red Sea Cucumber (*Parastichopus californicus*) harvest also provides significant income in BC (sea cucumbers, Fig. 4A) but there are no studies on OA effects for this species. Elsewhere, a single study found that sperm motility of a reef-dwelling sea cucumber species (*Holothuria* sp.) was impaired at pH values <7.7 [264]. Elevated P_{CO_2} and temperatures have been shown to have positive and additive effects on the relative growth of the keystone sea star

Pisaster ochraceus [265]. Under increased P_{CO_2}, calcification is reduced [265]; however, growth rate remains unchanged as the endoskeleton is primarily composed of soft tissue with relatively small calcareous elements for rigidity and protection. Brittle stars (ophiuroids) are commonly found in the region, but the effects of OA have only been studied in species found elsewhere. In the eastern Atlantic Ocean, keystone brittle star *Ophiothrix fragilis* was found to be especially sensitive to small changes in pH [266], with 100% mortality of larvae at pH 7.9 vs. 30% mortality in the control (pH = 8.1). Finally, while Dupont *et al.* [251] found that echinoderms stndied to date are relatively robust to OA effects, they conclnde that the overall impact of OA on this group will be negative and suggest that associated ecosystem impacts may be more severe.

Indirect effects Declines in some echinoderms may affect the predators that depend on them, but ecosystem effects remain unknown. For example, on our coast, various nearshore rockfish and numerous flatfish prey on ophiuroids [267], although they only form an important component of the diet for China Rockfish (*Sebastes nebulosus*), Flathead Sole (*Hippoglossoides elassodon*), and Southern Rock Sole (*Lepidopsetta bilineatus*) [267]. Additionally, the deep-water rockfish Longspine Thornyhead (*Sebastolobus altivelis*) relies on brittle stars for a large proportion of its food [268]. In the eastern Atlantic, the inevitable decline in pH may lead to the disappearance of the keystone brittle star *O. fragilis*; the impact on the ecosystem is not really known [266].

Echinoderm synopsis Although many echinoderms have not been studied, the existing evidence indicates significant negative effects due to OA, especially at early life stages. Thus, we suggest that this group will be affected negatively (Fig. 4A). Of more concern are the anticipated negative impacts on ecosystems, *e.g.* declines in the population of a keystone species like the Purple Sea Star would have wide-ranging effects on the food web.

Crustaceans

Marine crustaceans are represented in BC by copepods [269], krill (euphausiids) [39], barnacles [270], shrimps, prawns and crabs [271]. Copepods (see Mesozooplankton) and krill form a substantial biomass in the oceans and provide an important source of food for upper trophic levels in temperate marine foodwebs and act as important grazers (e.g., [272]). Crabs are found in the upper 50 m, while adult prawns (*Pandalus platyceros*) and adult shrimp (mainly Smooth Pink—*Pandalus jordani* and Sidestripe—*Pandalopsis dispar*) are deeper (~100 m and 120 m, respectively: Fig. 3). Krill, primarily *Euphausia pacifica*, perform strong diel vertical migration from the surface to depths exceeding 100 m. Krill is harvested on a limited basis in the Strait of Georgia and various inlets [39]. Prawns and shrimps, which are farmed extensively in other parts of the world, are only harvested from the wild in BC; the prawn fishery is substantial (~$40 million, Fig. 4) [34]. The crab fishery in BC is also valuable (~$33 million) [34, 273], with Dungeness Crab (*Cancer magister*) being the most important commercial species.

Direct effects Crustacean exoskeletons, composed of chitin and $CaCO_3$ [274], are generally considered to be unaffected by OA. In fact, evidence suggests that this protective covering actually serves as a buffer to the corrosive nature of OA, and some crustaceans can use the increased DIC in seawater to fortify their shells through calcification [275]. This enhancement of the shell contrasts with shell dissolution in molluscs (see Molluscs Section), and is likely due to some crustaceans (crabs, lobsters) having an efficient proton-regulating mechanism [275]. Despite the advantage of localised pH-regulation, the calcification response appears to depend on a variety of additional factors: external organic coatings, skeletal mineralisation composition (*e.g.* magnesium content in calcite), and the degree to which amorphous $CaCO_3$ (precursor to calcite/aragonite shells) is utilised [275–277].

Crustacean species' ability to deal with increasing OA also depends on life-history strategies and habitat [278]. Active species or those in highly fluctuating environments (*e.g.* intertidal or estuarine) tend to utilise the oxygen-transporting protein haemocyanin, which also confers additional buffering capacity against high H^+ concentrations. Sedentary species or those in stable environments (*e.g.* deep-sea or polar) tend to have less haemocyanin and consequently less buffering capacity. The latter group relies more on HCO_3^- buffering and is probably more sensitive to OA.[278]

Recent studies on Alaskan King Crab (AKC, *Paralithodes camtschaticus*) and Tanner Crab (TC, *Chionoecetes bairdi*) in Alaskan waters highlight the vulnerability of the early life stages to OA [279, 280]. For AKC embryos and larvae, OA produces larger embryos (but not larger mass), smaller egg yolks, higher developmental rates, and higher calcium content [280]. In juveniles of both species, increased mortality occurs with elevated P_{CO2} (Table 1), with 100% mortality in their most extreme treatment (S2 Table) [279]. Differences between the two Alaskan crabs (decreased condition index in AKC but not TC and decreased calcium content in TC but not AKC) suggest that AKC puts more energy into osmoregulation and calcification than does TC [279]. Additionally, there is some preliminary evidence that adnlt AKC females fail to moult [280].

Initial studies are underway on the dominant local species of krill, *Euphausia pacifica*. A recent study in Puget Sound, WA (Fig. 1), found that elevated P_{CO2} slowed the development of hatched nauplii to the first feeding stage (Anna McLaskey, pers. comm., University of Alaska, Fairbanks AK). Also, under higher P_{CO2} the Antarctic krill species, *Euphausia superba*, experiences ingestion rates 3.5 times higher than those under present-day conditions, and consistently higher metabolic rates [281].

For the cold-water barnacle, *Semibalanus balanoides* (common in BC), experimental treatments at elevated CO_2 (S2 Table) reduced adult survival and slowed embryonic development, which delayed the time of hatching by 19 days [282]. The cold-water shrimp, *Pandalus borealis* (common and commercially important in BC), also exhibited delayed juvenile development at reduced pH [283]. Other studies find no such delays [284–286], though significant effects have been observed when temperature and P_{CO2} interact [285]. The ability to tolerate OA also depends in part on prior exposure to habitats that experience highly fluctuating P_{CO2} [287].

Indirect effects Slow embryonic development [282] could potentially cause a timing mismatch between larval release and prey availability related to the spring phytoplankton bloom [288]. Potentially slower growth and lower fitness in juveniles and young adults may reduce egg production by females over their lifetime [279]. Despite the stability of adult exoskeletons, the post-moult calcification stage in crustaceans may be delayed significantly under elevated P_{CO2} [278], which may increase mortality due to predation on this defenseless life stage (*e.g.* [289]). Additionally, Kunkel *et al.* [290] hypothesise that OA may degrade the thin outer layer of calcite, which helps protect decapods from microbial attack. Finally, stock assessment models that incorporate reduced recruitment survival as a function of OA suggest that there can be a substantial socio-economic cost that is currenfly not recognised by decision makers [291].

Crustacean synopsis Generally, the crustaceans are expected to be sensitive to OA effects at early life cycle stages, while available studies suggest mixed results for adnlts. However, many local species, such as prawns, have not been studied (Fig. 4A). There is evidence that developmental anomalies in embryos and larvae occur at reduced pH, which may affect fhe fitness of juveniles and adults; however, the effects are species-specific and phenotypic adaptation is not known. Additionally, changes in growth rate and calcification may increase the susceptibility to predation, and delays in development may decouple life cycle timing between larval release and optimal foraging conditions.

Fish

In BC coastal waters, there are over 300 species of marine fish [292, 293]. The taxonomic groups represented in BC include jawless fish (*e.g.* hagfish (270–1010 m)), cartilaginous fish (*e.g.* ratfish (50–380 m), dogfish (50–430 m), sharks (90–1020 m), skates (50–860 m)), and bony fish. The latter group includes important contributors to BC fisheries—Pacific Herring (*Clupea pallasi*, 5–170 m), salmon (five species of *Oncorhynchus*, mostly in the surface 50 m but some species deeper than 100 m), Pacific Hake (*Merluccius productus*, 80–700 m), Pacific Cod (*Gadus macrocephalus*, 50–300 m), Walleye Pollock (*Theragra chalcogramma*, 50–300 m), rockfish (at least 36 species of *Sebastes* (70–470 m) and two species of *Sebastolobus* (160–1010 m)), Sablefish (*Anoplopoma fimbria*, 70–970 m), Lingcod (*Ophiodon elongatus*, 50–310 m), Arrowtooth Flounder (*Atheresthes stomias*, 60–600 m), soles and flounders (~ 18 species, 50–860 m), and Pacific Halibut (*Hippoglossus stenolepis*, 50–490 m). Depth distributions for valuable BC fisheries (Fig. 4) appear in Fig. 3. Marine fish species are economically important (GDP of capture fisheries, aquaculture, and sport fishing in BC was over $340 million in 2011 [29]) and ecologically valuable because of their roles providing food sources to higher trophic levels (*e.g.* birds and mammals) and cycling nutrients to other ecosystems (*e.g.* salmon providing nutrients to coastal terrestrial ecosystems [294]).

Direct Effects In general, we expect that adult fish will be tolerant of OA because they can control ion concentrations through evolved regulatory mechanisms [295, 296]. In particular, active fish exhibit transient elevated metabolic rates and highly variable extracellular CO_2 and proton concentrations. Acid-base imbalances are regulated by specialised gill epithelia, which compensate for pH disturbances caused by exposure to increased environmental P_{CO2} [296]. Although some studies suggest that aerobic performance of tropical fishes may decline under elevated P_{CO2} [297] (Table 1), detrimental effects were not found in a temperate species, Atlantic Cod, under elevated P_{CO2} (*e.g.* [295]).

The effects of lake acidification on diadromous fish (those migrating between marine and fresh water) are well known, but using these observations to suggest OA effects is potentially misleading due to (i) large physiochemical differences between fresh and acidified marine waters and (ii) high physiological variability between diadromous and marine species [298, 299]. Also, fluctuations in in $[H^+]$ seen in lake acidification are orders of magnitude greater than those in the ocean [298].

As with the invertebrates, OA effects in fish are expected to occur during the vulnerable developmental stage, and these effects appear to be species specific. The acid-base regulatory mechanisms of the larval stage remain rudimentary until gills have formed and respiration switches from cutaneous to branchial [300]. Developmental responses are thought to be more the result of CO_2 toxicity rather than through pH acting alone [301, 302].

There are limited OA studies on fish species that occur in our region. Hurst *et al.* [303] showed that the effects of OA on the growth of Walleye Pollock larvae were minor and varied greatly within treatments (S2 Table, Fig. 4). Slightly higher growth rates in elevated P_{CO2} conditions (Table 1) proved non-significant. Other studies on Atlantic temperate fish species (cod and herring), closely related to those in BC waters, found no significant effects on sperm motility, embryogenesis, egg survival, or the development of skeletal, heart, and lung tissue [300, 304, 305]. Despite these benign effects, researchers have found some developmental anomalies. Franke and Clemmesen [305] showed an inverse relationship for Atlantic Herring between P_{CO2} and the ratio RNA/DNA at hatching, potentially reducing protein biosynthesis and growth. Frommel *et al.* [300] found significant tissue damage in liver, pancreas, kidney, eye, and gut of Atlantic Cod larvae under elevated P_{CO2} Baumann *et al.* [306] demonstrated that increasing P_{CO2} caused a 74% reduction in survival and an 18% reduction in length of embryos of a ubiquitous estuarine fish called Inland Silverside (*Menidia beryllina*). Any significant developmental effect could alter the abundance and diversity of marine fish populations.

Otoliths (ear bones) are aragonite-based structures that fish use to sense acceleration and orientation. In some species, otoliths grow larger when larval fish are exposed to elevated P_{CO2} (*e.g.* White Sea Bass, a species found in BC waters [307]; Atlantic Cod [308] and tropical clownfish [309]). Under elevated P_{CO2} pH is regulated in the endolymph sac surrounding the otolith resulting in increased $CaCO_3$ precipitation and enhanced otolith growth for those species [309]. An increase in otolith size may enhance hearing range [310], which might help or harm fish depending on sensitivity to important auditory cues or disruptive background noise [310].

Behavioural responses have recently been documented at elevated P_{CO2} for larvae of tropical reef fish. In particular, behaviour to olfactory, auditory, and visual cues changes when larvae are selecting habitats and responding to predators [311–315]. Additionally, elevated P_{CO2} reduces learning abilities related to predator avoidance [316] and changes the propensity of larval reef fish to turn left or right (lateralisation) [317]. These behavioural changes can expose larval fish to increased mortality risk, which has important fitness consequences [313, 318]. Given possible behavioural effects on predators as well as prey under elevated P_{CO2} community-level responses are difficult to predict [318, 319].

Relatively few studies have investigated behavioural changes to OA in temperate species (three exceptions being [320–322]), and none have examined commercially important species in BC waters. The larvae of Threespine Stickleback (*Gasterosteus aculeatus*), a species found in marine and fresh water on the BC coast, exhibit behavioural disturbances (*e.g.* reduction in boldness and curiosity), compromised learning abilities, and declines in lateralisation when reared in elevated P_{CO2} [320]. These responses are surprising given the physiological plasticity of this species, which is expected to confer enhanced acclimatisation abilities to environmental challenges. These results suggest that sensitivity to OA is not limited to species occupying narrow ecological niches, such as tropical reef fish [320].

Elevated P_{CO2} can disrupt the functioning of $GABA_A$ (γ-Aminobutyric acid) receptors, the main inhibitory neurotransmitter receptors in the fish brain [323]. Normally, the opening of these receptors results in an inflow of Cl^- and HCO_3^- ions over the neuronal membrane, leading to inhibition of the neuron. When concentrations of intracellular Cl^- and HCO_3^- are altered (e.g. when fish with strong acid-base regulatory systems are exposed to higher environmental P_{CO2}, the flow of ions can be reversed, resulting in neuronal excitation instead of inhibition. Such changes have been associated with dramatic shifts in behaviour and sensory preferences in larval tropical reef fish [323], but the effects on temperate species are unknown. Although these receptors are shared by many, if not most fish, the resulting behavioural responses will likely vary due to species-specific differences in acid-base regulatory systems [323].

Indirect effects Fish will likely be affected indirectly by OA through food-web interactions. Off the southern WCVI, the pelagic system is dominated by Pacific Hake, Pacific Herring, Spiny Dogfish, and Chinook Salmon (*Oncorhynchus tshawytscha*), all largely dependent on krill production in the region [324]. This area has also been described as a "toxic hot spot" due to consistently high levels of *Pseudo-nitzschia* species and the presence of domoic acid [325]. These neurotoxins are transferred to higher trophic levels [59], and as P_{CO2} increases under OA the toxicity of these blooms may also increase [93].

Many fish species of the north Pacific Ocean prey on shelled pteropods (*e.g.* cod, pollock, mackerel) and a decline in pteropod abundances may lead to a shift in diet toward greater predation on juvenile fish such as salmon [326]. Pteropods (see Pteropods—Indirect effects) are also an important food source for Pink Salmon in the first year of marine life [166]. Because pteropods often exhibit swarming behaviour, foraging costs are relatively low for Pink Salmon feeding on patches [166, 180], possibly enhancing growth in early marine life and increasing adult biomass [327]. Reductions in pteropod densities may therefore have significant impacts on Pink Salmon biomass (Fig. 4A).

Trophodynamic modelling can suggest possible impacts of OA on fish populations. One study [328] explored various scenarios under OA, one of which assumes a significant mortality on benthic shelled invertebrates (*e.g.* bivalves, corals, sea urchins, sea stars) that leads to a biomass reduction for fish that feed on these species. While both English Sole (*Parophrys vetulus*) and small demersal sharks (*e.g.* Spiny Dogfish) rely on these invertebrates for only 10% of their diet in the model, English Sole experiences a much bigger decline due to a lack of alternative prey items. Another OA scenario in [328] adds an additional mortality on large zooplankton and small phytoplankton, which leads to a large increase in microzooplankton, detritus, and bacteria. In this scenario, the model predicts various higher-order interactions: a reduction of Lingcod due to a decline in macrozooplanktonic prey; an increase in Canary Rockfish (*Sebastes pinniger*) due to an increase in sea urchins and shrimps; and the increase of nearshore rockfish due to a decline in one of its predators, Lingcod. While there are many possible outcomes using such modelling tools, they do highlight how effects from OA on any single biological component can affect the entire trophic web.

Fish synopsis In general, we expect that adult fish will be tolerant of OA because of their ability to control internal ion concentrations. However, OA may affect fish during vulnerable developmental stages, though evidence for these effects is weak for species in BC. Perhaps more importantly, behavioural responses to OA have been widely documented in tropical reef fish, resulting in reduced survival. Similar effects may occur in temperate species, though studies in this area are limited. OA-induced reductions in availability of some prey species may reduce fish growth and survival, though these effects may be tempered by prey-switching. Possible increases in HABs would have a negative impact on farmed fish and shellfish; wild fish might increasingly suffer the effects of biotoxin accumulation.

Marine mammals

British Columbia is host to a large and diverse group of marine mammals (~30 species [329]), many of which have experienced dramatic population increases over the last century when hunting and culling practices were discontinued (*e.g.* on Grey Whales (*Eschrichtius robustus*) and Harbour Seals (*Phoca vitulina*), respectively) [330]. In addition to their role as top predator in the marine food web and their contribution to ecotourism, these mammals are iconic symbols of the region. Thus, they are valuable, but their value is difficult to assess (*e.g.* [331]).

In general, marine mammals cover an appreciable geographic range and many are able to dive to remarkable depths [332]. Their physiology is adapted to high pressures and they have an exceptional capacity for O_2 [332]. Because they breathe at the surface, they are not susceptible to acidosis in the way that many other complex marine organisms will be as carbon levels increase (*e.g.* [302]). Therefore, direct impacts of OA on marine mammals are not expected, and have not been investigated (Fig. 4A). Indirect food web impacts are anticipated, *e.g.* for cetaceans that rely heavily on cephalopods or zooplankton such as pteropods [333]. In addition, underwater sound absorption at low frequencies (relevant for marine mammals) will decrease with OA [334]. However, this decrease is projected to be small (less than 0.2 dB) over the next few centuries and negligible in the context of the current noise associated with shipping [335].

Marine mammal synopsis Marine mammals will likely be affected by OA indirectly through food web changes, however direct impacts are not anticipated. While noise levels will increase with OA, this increase will not be large enough over the next few centuries to affect animals that rely on underwater sound.

Discussion

We have described the marine ecosystem in the temperate coastal northeast Pacific region at present, and then its response to OA. However, the available information is limited. For some organisms, no OA studies exist (*e.g.* Geoduck Clam, rockfish, S1 Table). In general there are more studies, with respect to distributions and OA impacts, on species that are easier to observe, are of commercial value (*e.g.* oysters, S1 Table) or that threaten human health (*e.g.* harmful algae, S1 Table). The results of studies like these are often adopted when similar research on native organisms is not available (as we have done), limiting the ability to predict responses with confidence. Furthermore, OA is only one aspect of climate change and predicting shifts in marine ecosystems, and the degree to which they are caused by natural or anthropogenic forcing, is a highly complex problem. In the following, we discuss these and other issues that influence our evaluation.

Caveats The number of studies related to OA is growing rapidly (*e.g.* S1 Table). While experiments in these studies are highly valuable, translating their results into changes in the real world is challenging. For example, wild populations of marine organisms will adapt (both physiologically in a single lifespan and genetically over multiple generations) to their changing environment, which is difficult or impossible to capture *in vitro*. However, using temperature-dependent adaptation as a guide, Kelly and Hofmann [336] caution that the ability to adapt to changing pH may be limited.

In addition, food-web interactions and responses to OA are extremely difficult to predict, but will influence marine populations and could tip the balance from an overall negative impact to a positive one for a given species if a key predator is removed. Ecosystem effects resulting from OA have previously been identified as a key knowledge gap [337]. Furthermore, different life stages, particularly the juvenile stage (*e.g.* echinoderms), often display increased susceptibility to OA, but the impact of exposure of one life stage to low pH conditions on the subsequent life stages has only rarely been studied (but see [206, 212]). Similarly, even in organisms that have been comparatively well studied, not all life stages have been considered and certainly not within the context of the variability in natural conditions (Fig. 2).

Manipulated experiments generally consider present-day atmospheric conditions ($\sim$360–400 μatm) to be the control P_{CO_2} level and all treatments above that to be 'elevated'. Meanwhile P_{CO_2} varies significantly with depth, and is naturally high in the north Pacific [28]. We quantify 'elevated' based on the local P_{CO_2} levels at the depths of the organisms in question (Table 1). The combined effect of coastal upwelling, and local remineralisation of high production [27], results in exceptionally high (and variable) subsurface P_{CO_2} on the outer BC shelf (Fig. 2). In local and connected inshore waters subsurface P_{CO_2} is also high (unpublished data, DI; [6, 31]). Thus, many marine organisms in our region are currently experiencing conditions that are viewed as 'elevated' in the literature (Fig. 2; S2 Table). In addition, laboratory treatments often specify environmental conditions (*e.g.* temperature, P_{CO_2}) that do not occur in nature and are unlikely to occur, at least locally (*e.g.* [31]). Exposure time may also limit the interpretation of results, as there are distinct differences between treatments that are 'shocked' and those that are allowed to acclimate (*e.g.* [87, 248]).

Finally, defining the carbon state in seawater is not trivial [10] and requires that at least two of the four carbon parameters (DIC, TA, P_{CO_2}, pH) be measured. The quality of the measurements and manipulation in the laboratory work cited here is variable. While the high degree of accuracy and precision required by chemical oceanographers [10] is in general not necessary to obtain insight from biological manipulation experiments, the equations that define the carbon system lead to compounding errors when calculating one of the unknowns. Thus, a moderate uncertainty in P_{CO_2} may translate to an estimated pH that has little, or no meaning. We urge the reader to consult S2 Table where all available detail for each experiment cited has been summarised.

Climate change—the whole picture The ocean has absorbed a significant portion of the anthropogenically produced carbon [2] and that has caused on average a 30% change in surface ocean acidity [5]. However the annual variability in surface P_{CO_2} and pH in dynamic regions like the BC [24] and WA [31] coasts is generally more than two orders of magnitude greater than the annual atmospheric increase in CO_2. In other words, we expect the OA trend to be present, but overlaid is a signal with large amplitude.

Climate change may alter this dynamic natural cycle so that negative impacts associated with high acidity are experienced earlier in the coastal northeast Pacific than elsewhere, regardless of OA. There are critical times during the year when carbon conditions (particularly in the upper mixed layer; 20–30 m on the outer coast; ~ 10 m or less in protected waterways) change dramatically. For example, the spring bloom in the Strait of Georgia causes a large and rapid increase in surface pH (Ben Moore Maley pers. comm., University of British Columbia, Vancouver BC) and the timing of this event varies significantly from year to year [338]. On the outer shelf, the onset of summer upwelling brings lower pH water over the continental shelf and decreases pH (on average) throughout the entire water column. Climate change may alter the strength, timing [339–341], or even the variability in the timing, of such events. Thus, the influence of climate change on weather may play a critical role, that will only be exacerbated as OA progresses.

In addition to changing weather, sea surface temperatures are expected to increase and subsurface O_2 is expected to decrease (leading to increased occurrence of hypoxia) with climate change, concurrent with OA. Temperature has a large effect on marine organisms because metabolism increases as the ocean warms, consequently increasing energetic costs. As a result, changes in present-day distributions of marine organisms have already been linked to changes in temperature [342]. Thus, a 'multi-stressor' approach is required to understand the net effect of climate change on marine organisms. The net effect of all three stressors (warming, hypoxia and OA) may be synergistic and has been generally described as a narrowing of the thermal ranges in which organisms can perform well, and a decrease in maximal performance [343]. Lastly, changes in human behaviour (*e.g.* fishing) as climate change and OA progress may also play an important, and possibly additive, role in shaping future marine ecosystems (*e.g.* [344]).

Conclusions

There remain significant knowledge gaps with respect to the biological impacts of OA on marine ecosystems globally, and locally. The most critical impacts will likely be indirect as a result of food web changes, and so are highly complex and difficult to predict even with extensive study. Furthermore, OA related changes will occur in concert with other climate change impacts that may be even more severe (see above). In particular, increasing temperature and decreasing dissolved oxygen are likely to produce synergistic effects.

The northeast Pacific region naturally has waters low in pH (undersaturated with respect to aragonite) near the surface. Thus, it is potentially more vulnerable to OA than other regions. We summarise the most relevant risks and identify key knowledge gaps, given present-day knowledge, to Pacific Canadian fisheries and marine ecosystems in the order of immediacy and certainty.

- Shellfish aquaculture is highly susceptible to OA due to the direct impact of OA on shell formation and the dependence of the industry on hatchery production. These impacts are already experienced in BC (and WA). Wild shellfish experience similar difficulties but have the opportunity to adapt (*e.g.* [197]) and so will likely not be affected as rapidly and severely.

- There are no studies on Geoduck Clams, which are responsible for a lucrative wild fishery and a growing aquaculture industry in BC (although the latter is still in its infancy).
- The commercial BC fishery is dominated monetarily by salmon aquaculture. While uncertainty remains low, it is anticipated that the fish-killing alga *Heterosigma akashiwo* will gain a competitive advantage under OA, making blooms more frequent. Such blooms are already a significant issue for this industry in BC.
- Neurotoxins produced by other harmful algae are expected to become more potent under OA. Such blooms already cause shellfish closures in BC. If this increase in toxicity occurs, the shellfish industry will be affected. In addition, these toxins may cause decreased reproductive success, and even mass mortality, at higher trophic levels including fish, seabirds and marine mammals.
- Food web changes due to OA (*e.g.* in BC changes in the species composition of phytoplankton and decline of pteropods) are anticipated but remain unknown, as are the impacts of these lower level changes on higher trophic levels.
- Finfish are likely to experience OA impacts through foodweb changes. In BC examples include: the decline of pteropods, that are directly preyed upon by some fish (particularly Pink Salmon), and the anticipated decline of some echinoderms, that are eaten by various species of rockfish aud flatfish.
- Habitat changes may also have a critical negative impact, in particular for juvenile fish. While these impacts remain highly uncertain, there may be a shift from upright macroalgae to algal turf. Also, local coral species (in BC primarily octocorals) that provide vertical structure may decline. Direct impacts of OA on finfish may also occur, but only at relatively high levels of CO_2.
- There are few direct OA studies on local finfish species and none on Pacific Halibut and salmon, which drive the sport fishing industry. Similarly there are no studies on the adaptation of these local species to OA and multiple stressors, like temperature and O_2, that will be changing at the same time. Because sport fishing dominates fishery related income in BC, this knowledge gap is significant.
- Behavioural changes at various trophic levels have been observed (*e.g.* increased downward swimming in phytoflagellates, decreased detection and avoidance of predators in larval fish) and postulated (*e.g.* increased movement to OA refugia such as eelgrass meadows). Such behavioural changes might alter the structure of marine communities in BC, and present another knowledge gap.
- Crabs may experience negative impacts under OA while other crustaceans significant to the harvest fishery in BC, like prawns, have not been well studied but appear to be more strongly sensitive to temperature than OA. In general, the juvenile stages of crustaceans are most vulnerable to OA, growing more slowly because they need to expend more energy under OA.

Supporting Information

S1 Table. Number of articles by Group of Organisms. Number of hits by Web of Science for OA-related studies on different groups of animals in March 2013 and March 2014.
(PDF)

S2 Table. Experimental details for manipulation experiments. The experimental details for all manipulation experiments referred to in this document.
(PDF)

S3 Table. Environmental details for *in situ* studies. Details (e.g. species, location, and carbon state) for OA-related *in situ* studies of marine organisms.
(PDF)

S1 Text. Pacific Region Animal Use Protocols. Marine animal use protocols in British Columbia, Canada.
(PDF)

S1 Data. Species depth distribution data. The data required to generate Fig. 3.
(XLSX)

S1 Code. R-code to create Fig. 1. The header within the code contains necessary instructions.
(R)

S2 Code. R-code to create Fig. 2. The code includes the data required to generate the figure.
(R)

S3 Code. R-code to create Fig. 3. The S1 data are required to generate this figure.
(R)

S4 Code. R-code to create Fig. 4. The code includes the data required to generate the figure.
(R)

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Author Contributions

Conceived and designed the experiments: DI RH CH AE. Performed the experiments: RH CH DI AE HN. Analyzed the data: DI RH CH AE. Wrote the paper: DI RH CH AE.

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This is Exhibit H
referred to in the Affidavit
of Tom Lesiuk #2
sworn before me this 18th day
of December 2014

A Commissioner for taking Affidavits
within British Columbia

POTENTIAL IMPACTS OF CLIMATE CHANGE ON BC HYDRO-MANAGED WATER RESOURCES

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Frank Weber, M.Sc., P.Geo., Hydrometeorologic Field Programs Engineer

Updated July [illegible]

BC hydro
FOR GENERATIONS

EXECUTIVE SUMMARY

Global climate change is upon us. Both natural cycles and anthropogenic greenhouse gas emissions influence climate in British Columbia and the river flows that supply the vast majority of power that BC Hydro generates. BC Hydro's climate action strategy addresses both the mitigation of climate change through reducing our greenhouse gas emissions, and adaptation to climate change by understanding the risks and magnitude of potential climatic changes to our business today and in the future.

As part of its climate change adaptation strategy, BC Hydro has undertaken internal studies and worked with some of the world's leading scientists in climatology, glaciology, and hydrology to determine how climate change affects water supply and the seasonal timing of reservoir inflows, and what we can expect in the future. While many questions remain unanswered, some trends are evident, which we will explore in this document.

WHAT WE HAVE SEEN SO FAR

- Over the last century, all regions of British Columbia became warmer by an average of about 1.2°C.
- Annual precipitation in British Columbia increased by about 20 per cent over the last century (across Canada the increases ranged from 5 to 35 per cent).
- For the period of inflow records (35 to 47 years, depending on the reservoir), there is some evidence of a modest historical increase in annual inflows into BC Hydro's reservoirs but trends are small and statistically not significant.
- Fall and winter inflows have shown an increase in almost all regions, and there is weaker evidence for a modest decline in late-summer flows for those basins driven primarily by melt of glacial ice and/or seasonal snowpack.
- The severity of year-to-year variation in annual reservoir inflow has not changed.

LOOKING INTO THE FUTURE

Projected changes in climate and hydrology are for the 2050s (unless stated otherwise) under different future emission scenarios.

- Projected warming in the 21st century shows a continuation of patterns similar to those observed in recent decades.
- All emission scenarios project increasing temperatures in all seasons in all regions of British Columbia.
- The amount of warming in the 21st century will very likely be larger than that of the 20th century.
- Precipitation in winter, spring, and fall will likely increase in all of BC Hydro's watersheds under all emission scenarios.
- BC Hydro will likely see a modest increase in annual water supply for hydroelectric generation.
- Most Upper Columbia watersheds will see an increase in water supply. The snowmelt will start earlier, spring and early-summer flows will be substantially higher, and late-summer and early-fall flows will be substantially lower.
- The Peace region will see an increased water supply. Inflows in late-fall and winter will increase; the snowmelt will begin earlier; and summer flows will be lower.
- The Campbell River area and likely most Coastal watersheds will see negligible changes to annual water supply.
- On the South Coast (Vancouver Island and Lower Mainland watersheds), more of the precipitation will fall as rain and snow will become less important. Fall and winter flows will increase; and spring and summer flows will decrease.

Hydrological impact studies are the first step in BC Hydro's climate change adaption strategy. In the next step, BC Hydro will evaluate how the projected hydrological changes may impact hydroelectric power generation.

INTRODUCTION

More than 90 per cent of the electricity in British Columbia comes from falling water. The amount of available water is directly affected by variations in climate. Land use, volcanic activity, ocean circulation, solar cycles, and the composition of the atmosphere all influence the global climate. An understanding of climate change, and its effect on the water cycle, along with information related to future economic activity and load growth, is critical to ensuring a reliable supply of hydroelectric power for generations to come.

Climate change is natural in both the short and long term (Figure 1). Among the most influential short-term events are ocean circulation patterns, such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), which fluctuate on yearly and multiyear timescales as they exchange heat between the oceans and the atmosphere. In the long term, changes in the Earth's orbit around the sun trigger ice ages every 100,000 years or so. Other cycles operate on the scale of millions of years.

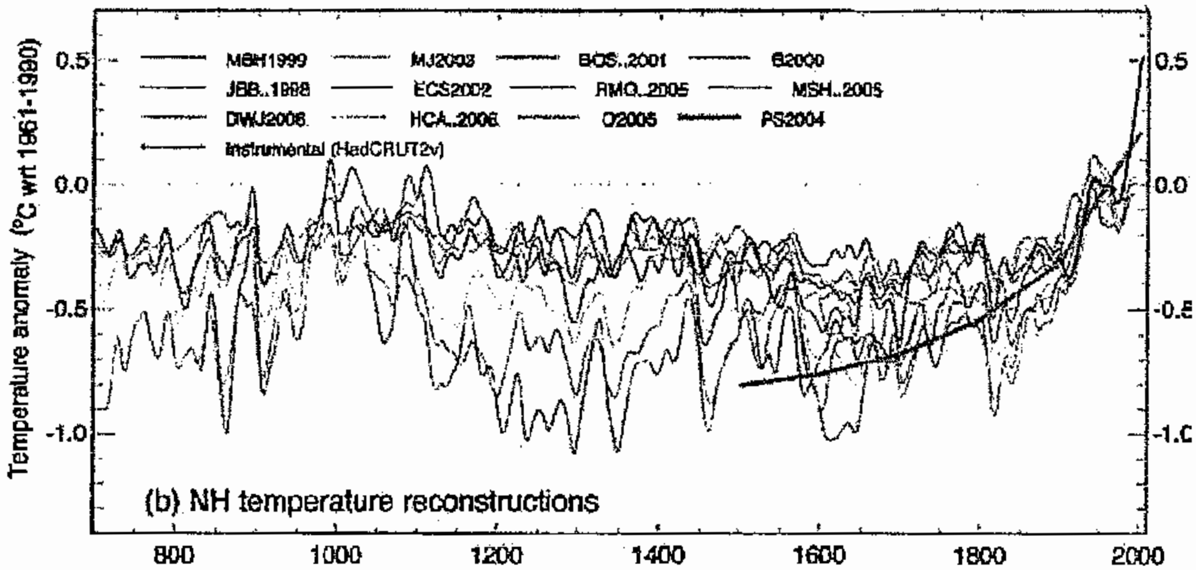


Figure 1: Northern Hemisphere warming based on a variety of reconstruction techniques (coloured lines) and instrumental record (black line). Source: IPCC 4AR: Climate Change 2007. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-6-10.html

The recent warming trend associated with rising concentrations of greenhouse gases (GHG) that trap heat in the atmosphere is, however, taking place at an unprecedented rate. The scientific evidence that this trend is at least partially caused by the emissions produced by burning fossil fuels, and is likely to continue for many decades, is compelling. In its 2007 Fourth Assessment Report, the UN Intergovernmental Panel on Climate Change (IPCC) concluded that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations."

Since about A.D. 1860, temperature records from surface weather stations show an increase of about 1°C over the Northern Hemisphere. Although precipitation records are less reliable, climatologists agree that precipitation over North America has increased by about 10 per cent during the 20th century. Understanding the impact of these accelerated changes is crucial for planning adaptive strategies.

DESCRIBING UNCERTAINTY

Uncertainty in specific outcomes in the body of this report is assessed using expert judgments and expressed with the following probabilities of occurrence:

- very likely >90%
- likely >66%
- more likely than not >50%
- about as likely as not 33% to 66%
- unlikely <33%
- very unlikely 10%

DEFINING "CLIMATE CHANGE"

This document uses the U.N. Intergovernmental Panel on Climate Change definition of climate change, which is "a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity."

HOW CLIMATE AFFECTS WATER SUPPLY

Precipitation can fall as rain or snow. It can return to the atmosphere through evaporation, replenish groundwater aquifers, or run off into streams, rivers, and oceans. Higher temperatures increase evaporation, which in turn alters both precipitation and runoff. In humid regions, more precipitation will likely result in more runoff. In drier regions, extra precipitation tends to evaporate, causing only small changes in runoff. While the effects of a changing climate may reduce water supply in some regions, it could also increase supply elsewhere.

Thanks to the size and geography of the province, BC Hydro has a diverse portfolio of hydroelectric facilities in various climate zones. This, and the large storage capacity in the Peace and Columbia River reservoirs, offers some flexibility to adjust to changes in water supply and reservoir inflows. Still, a rapidly changing climate could challenge that ability to adapt.

BC HYDRO'S CLIMATE ACTION STRATEGY

As part of the province's target of cutting GHG emissions by a third from 2007 levels by 2020, BC Hydro has prepared a climate action strategy with two key objectives:

» Maintain a low-carbon electricity supply for our customers; and

» Leverage that supply to support provincial GHG reduction targets and policies for a low-carbon economy.

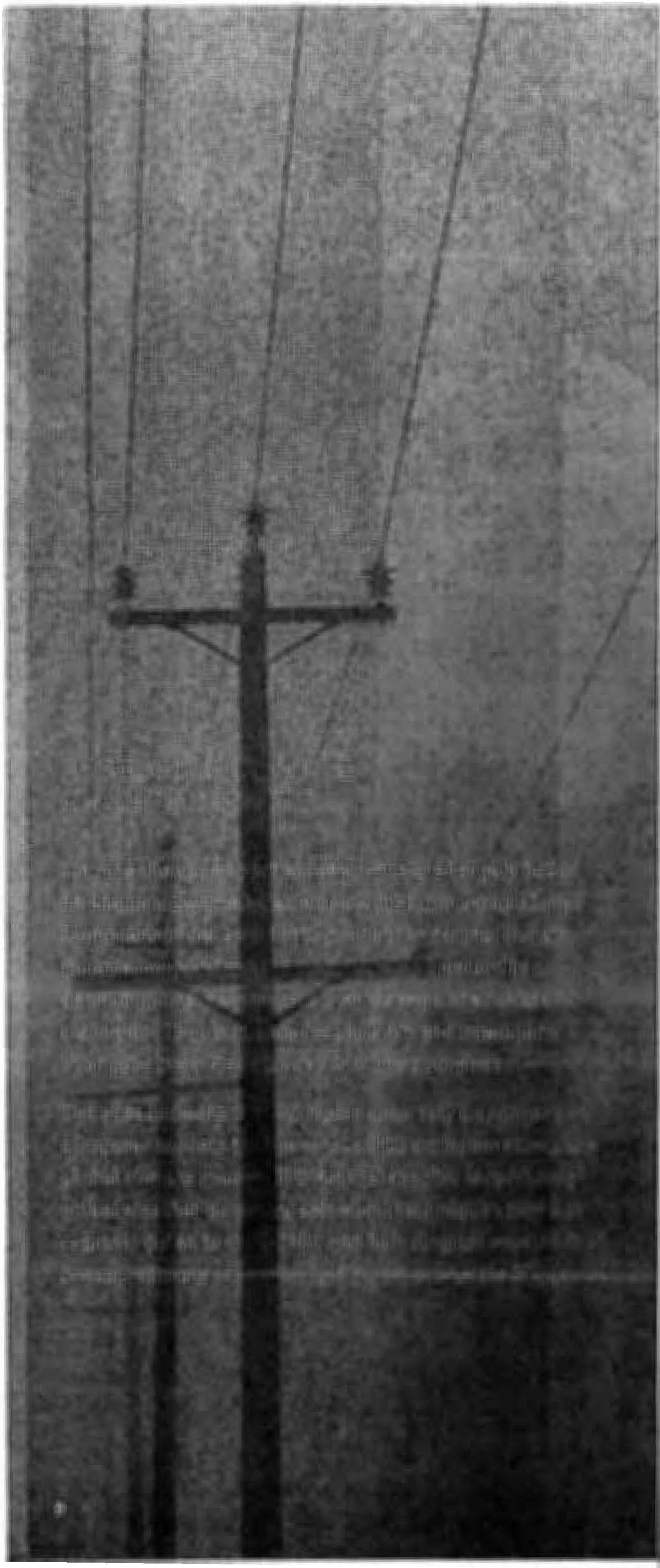
The strategy considers the potential effects of climate change in B.C., including increases in temperature, new precipitation patterns, and a greater frequency of floods, droughts, and wildfires. Changes in the timing and volume of spring runoff have implications for hydroelectricity generation. BC Hydro will incorporate these potential impacts, and adapt its infrastructure to accommodate the unavoidable.

BC HYDRO COLLABORATES WITH LEADING SCIENTISTS TO ASSESS IMPACTS OF CLIMATE CHANGE

As part of its climate change adaptation strategy, BC Hydro has undertaken internal studies and worked with some of the world's leading scientists in climatology, glaciology, and hydrology. BC Hydro teamed up with scientists from the Pacific Climate Impacts Consortium (PCIC) at the University of Victoria; the Western Canadian Cryospheric Network (WC2N), which consists of six Western Canadian and two Washington state universities; and the Climate Impacts Group (UW-CIG) at the University of Washington.

Hydrologists at BC Hydro conducted studies to investigate historic impacts of climate change on reservoir inflows. PCIC assessed historical and future trends in climate across British Columbia and projected future reservoir inflows in three distinct regions critical to BC Hydro's hydroelectric capacity: the Upper Columbia region, the Peace region, and the Campbell River region (Figure 2). The WC2N study quantified the magnitude and timing of glacier melt contributions to inflows into Kinbasket Reservoir (Mica basin) under a changing climate. The UW-CIG study assessed the hydrological impacts of climate change for the entire Columbia River basin in both Canada and the US (without accounting for effects of glaciers).

Figure 2: Regions with BC Hydro watersheds and representative watersheds for each region (Columbia basin with Mica highlighted=yellow, Campbell River at Strathcona=pink, Williston=brown, other BC Hydro basins=green).



ASSESSING CLIMATE CHANGE IMPACTS

Climate change impact assessments are largely based on scenarios—stories about how the future could look. Scenarios do not attempt to predict the future, but aim to better understand the uncertainties involved in making decisions, to accommodate a wide range of possible outcomes. They also help researchers and managers anticipate the consequences of those decisions.

The assessments that BC Hydro uses rely on numerical computer models that generate GHG emission scenarios, global climate models (GCMs) that resolve large-scale global weather patterns, statistical techniques that add regional detail to the GCMs, and hydrological models that convert climate scenarios into runoff scenarios (Figure 3).

EMISSION SCENARIOS

Projections of GHG emissions are based on storylines of demographic, social, economic, technological, and environmental developments. Future projections of climate and reservoir inflows were obtained by using three different IPCC emission scenarios. The so called B1, A1B, and A2 emission scenarios define futures with low, medium, and high increases in greenhouse gas concentrations, respectively When the IPCC scenarios were developed in the late 1990s, all were considered equally likely. However, the actual emissions growth rate since then is closer to or greater than the most fossil-fuel-intensive scenario.

GLOBAL CLIMATE MODELS

Global climate models represent physical processes in the atmosphere, in the oceans, and on land. They broadly reproduce historical climate at global scales, but are less successful at regional and local scales. The resolutions are such that any processes occurring on scales less than several hundred kilometres, such as the effects of mountain ranges and coastlines on cloud formation, are only roughly approximated. Statistical techniques bridge the gap between global climate and regional impacts, but at the price of higher levels of uncertainty.

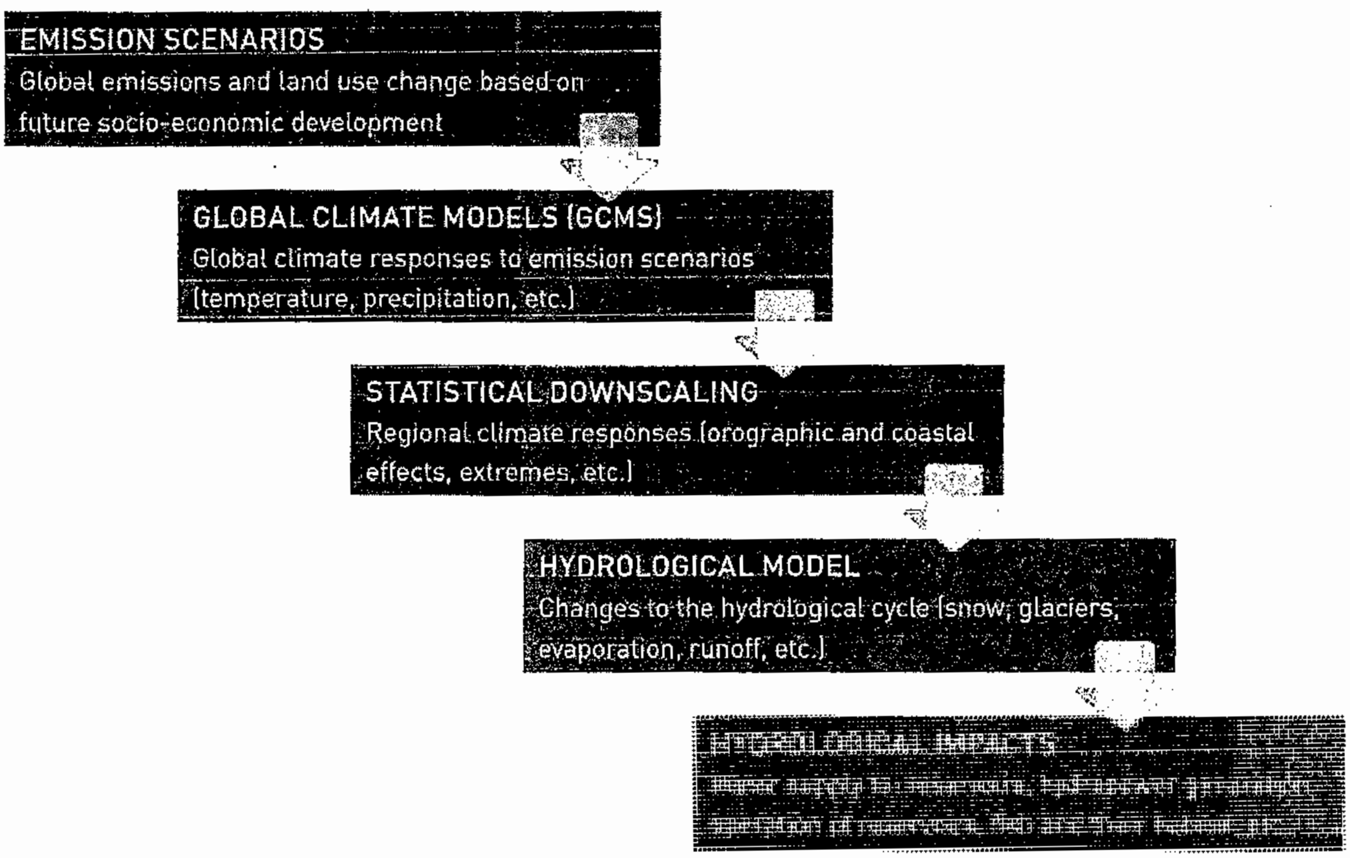


Figure 3: Method for quantifying hydrologic impacts under projected future climates.

OBSERVED TRENDS IN CLIMATE AND HYDROLOGY

HISTORICAL TRENDS IN TEMPERATURE AND PRECIPITATION

Between 1900 and 2004, B.C. saw wetter conditions and an increase in the average annual temperature of about 1.2°C. Most of the increase was a result of higher minimum temperatures (Figure 4).

Annual precipitation increased by about 20 per cent (Figure 4). Most of the precipitation increase occurred in fall, winter, and spring, with the highest increases in the northern interior and no change in the southwest (Figure 5).

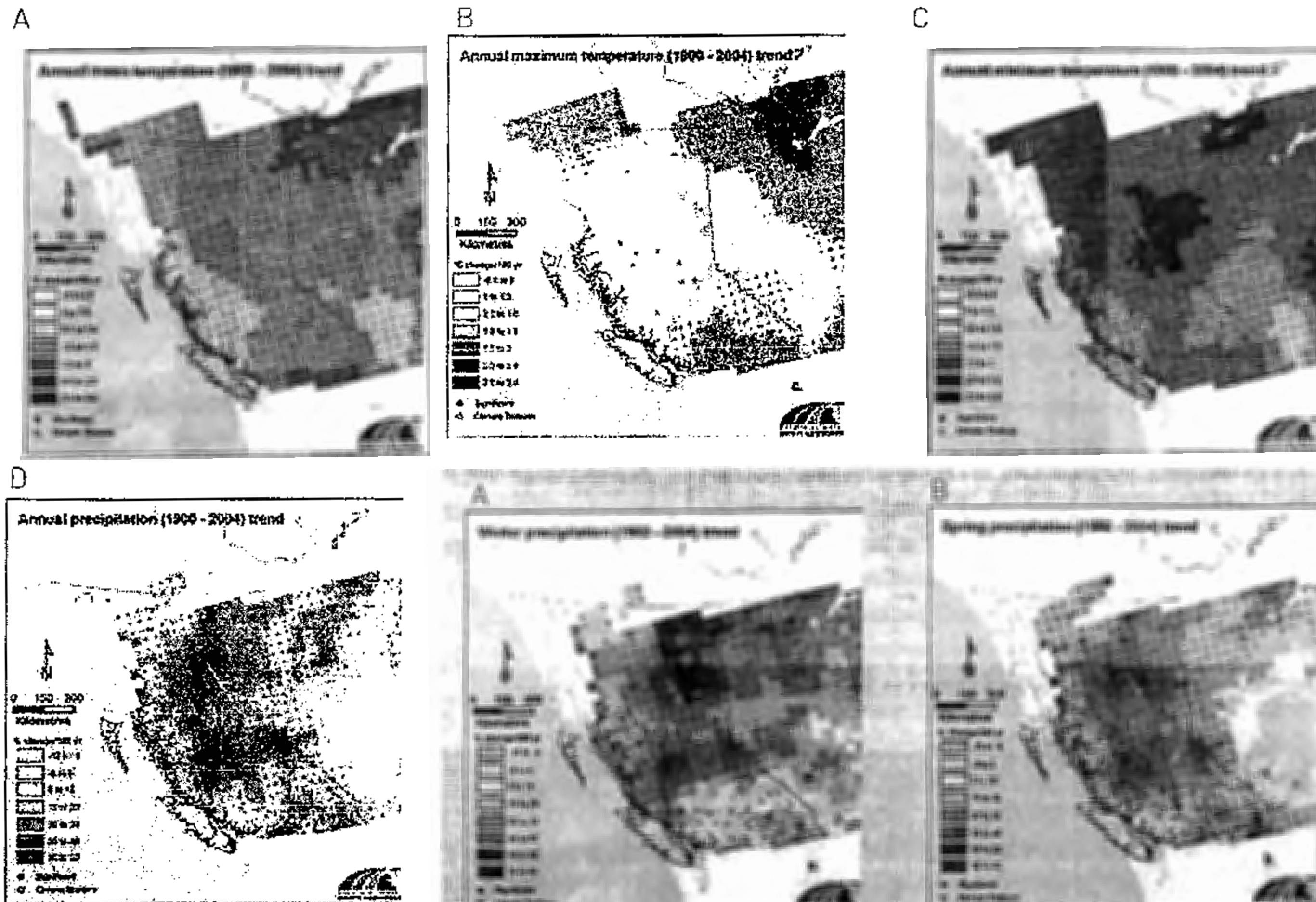


Figure 4: Annual mean temperature and precipitation trends for the 1900-2004 period (Rodenhuis et al. 2007)

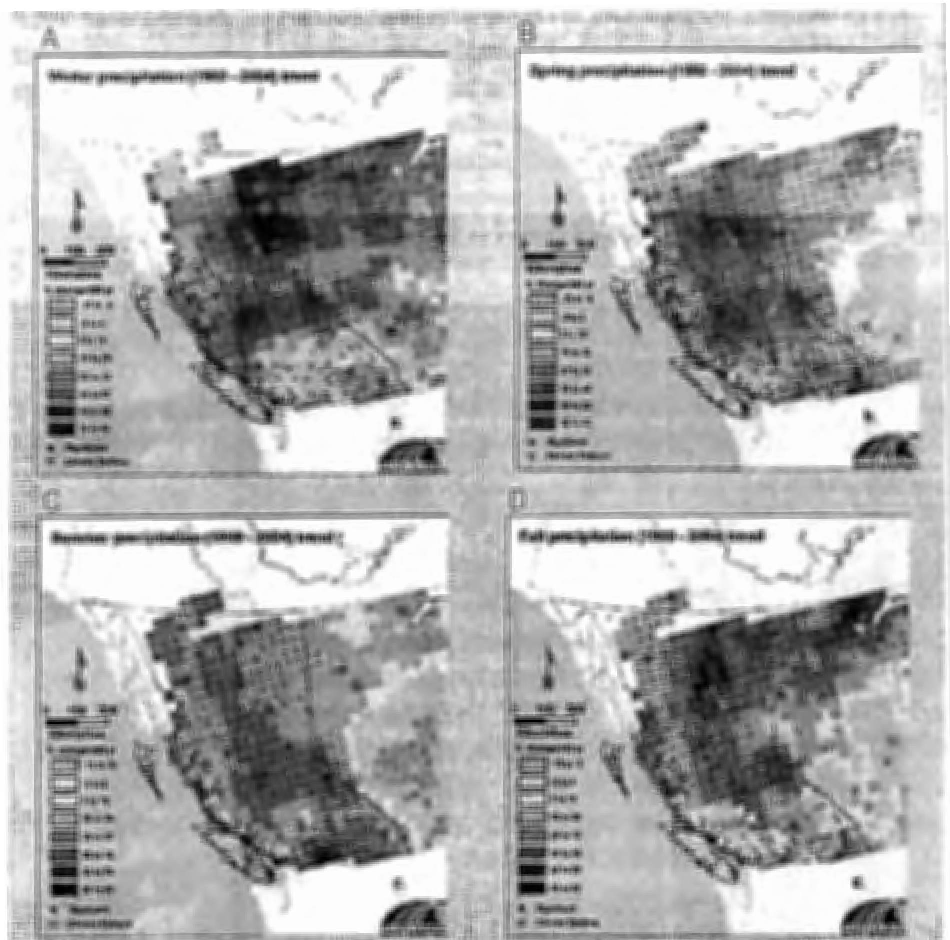


Figure 5: Seasonal precipitation trends for the 1900 to 2004 period (Rodenhuis et al. 2007)

CHANGES TO THE SNOWPACK

Precipitation that falls as snow is temporarily stored in seasonal snowpacks or glaciers. For many BC Hydro watersheds, basin-wide snow storage is larger than reservoir storage. A snowpack's water content is reported in millimetres of snow water equivalent (SWE). SWE on April 1 is often used as a proxy for the maximum snow accumulation of a year, although the timing of peak accumulation timing can vary at individual locations.

Records show a substantial reduction in peak winter snow accumulation over the past 50 years. On average across British Columbia, the peak SWE of 73 long term snow courses dropped by about 18 per cent. The Columbia region showed a 20 per cent reduction, the Kootenay fell by 23 per cent, and the South Coast and Vancouver Island dropped by 17 per cent. The Middle Fraser region experienced a 47 per cent reduction, while the Peace showed no notable changes and a few northerly locations recorded increases in SWE.

One-half to two-thirds of the reduction in peak SWE over the past 50 years is tied to natural ENSO and PDO cycles, with the PDO shift from a cold to a warm phase in 1976 having the most significant effect. After removing the effects of this natural climate variability, the province-wide SWE trends become very small, with a snowpack decline of just four per cent (Table 1). In some regions, adjusting for ENSO and PDO reverses the trend.

An important limitation of SWE analysis is that most of the observing sites are at mid elevations. Models suggest that the colder, highest elevations, which are less sensitive to warming, have seen an increase in peak SWE due to increases in precipitation.

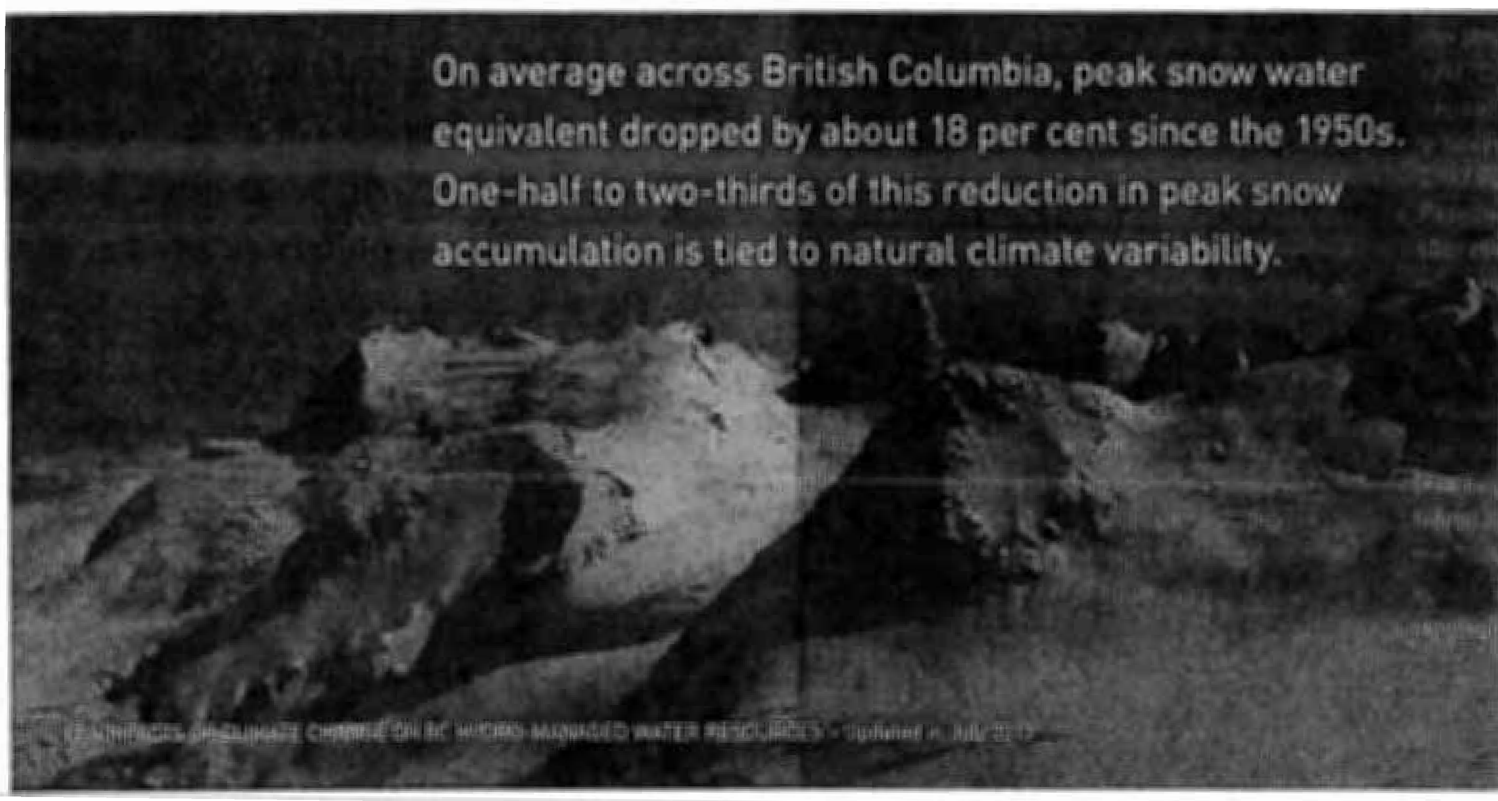
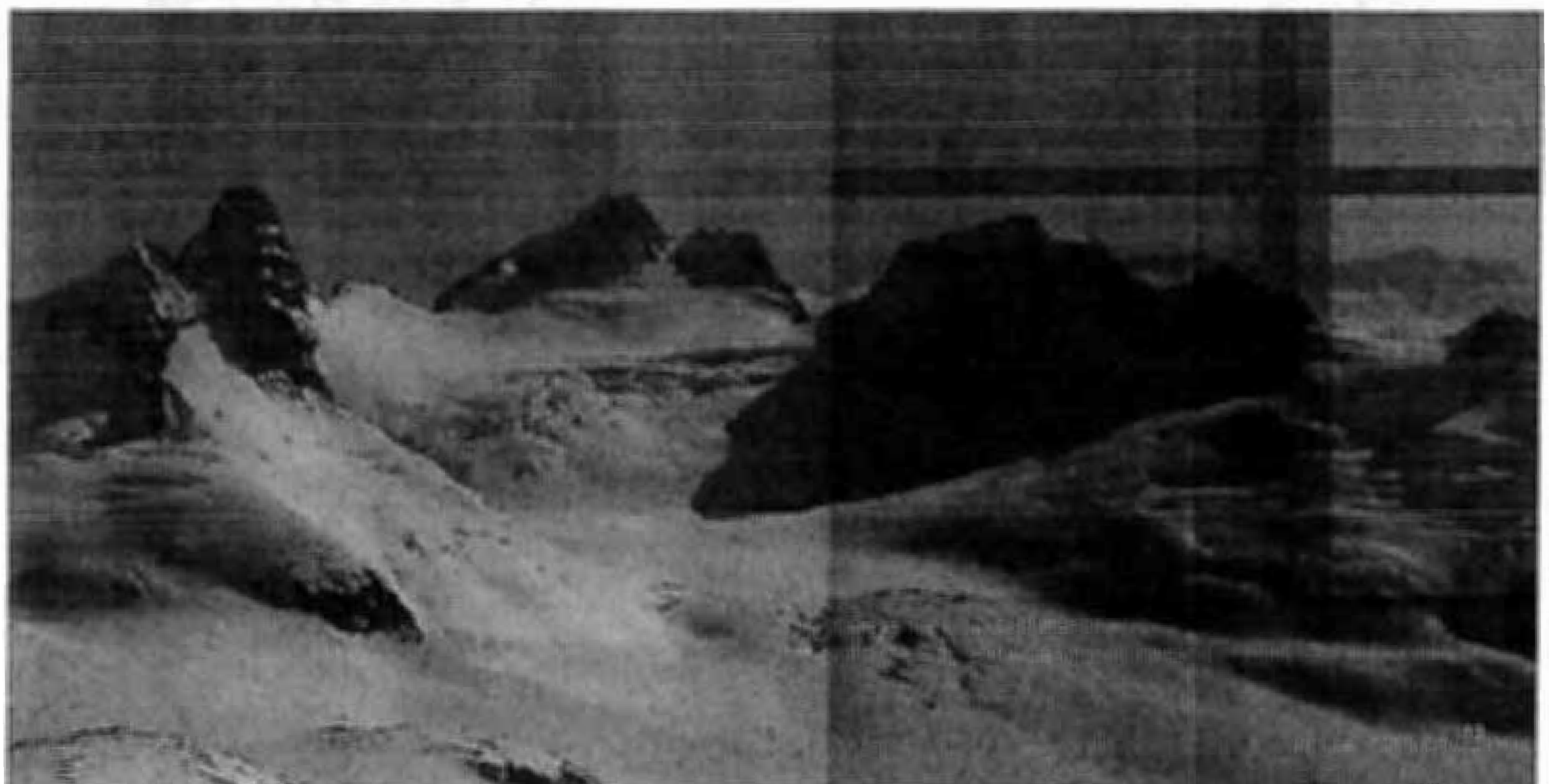


Table 1: Trends in April 1 Snow Water Equivalence at British Columbia long-term snow courses (1956-2005).
* Results are shown for unadjusted data and data with the effects of ENSO and PDO variability removed (Chapman, 2007).

BASIN / REGION	UNADJUSTED DATA Mean (mm)	UNADJUSTED DATA Change (mm)	UNADJUSTED DATA Change (%)	ADJUSTED DATA* Change (mm)	ADJUSTED DATA* Change (%)
Peace	399	-8	-4	33	7
Columbia	646	-87	-20	7	-5
Kootenay	365	-91	-23	-21	-6
Middle Fraser	213	-82	-47	-31	-27
South Coast/ Vancouver Island	1202	-261	-17	-65	-4
British Columbia (overall)	474	-71	-18	0	-4

% Change Key: little or no change: -5% and 5% increase: > 5% decrease: < -5%



GLACIER CHANGE

A change in glacier cover provides visually compelling evidence of the effects of climate change on the water cycle. Glaciers across the province lost about 11 per cent of their area between 1985 and 2005. Coastal glaciers lost less area than interior glaciers, but absolute volume loss was larger in the Coast Mountains than in the Columbia region or the Rocky Mountains. In the Columbia River basin, glacier cover declined by about 16 per cent from 1986 to 2000. Glaciers thinned most at lower elevations. Figure 6 illustrates the retreat of the Illecillewaet Glacier at Roger's Pass between 1887 and 2000.

Glaciers cover approximately 25,000 km² of British Columbia which is just three per cent of the total surface area. At the scale of watersheds operated by BC Hydro, the impact of glacier melt on annual flow volumes is relatively minor. However, even a glacier cover of five per cent, such as in the Mica basin, can contribute significant flow in the late summer. During the warm and dry summer of 1998, for example, glacier melt contributed 35 per cent to the Mica basin's September streamflow. With a warming climate, those contributions will very likely decrease as glaciers retreat.

Figure 6: Extent of Illecillewaet Glacier at Roger's Pass (Selkirk Mountains) in the Arrow watershed in 2000, with lines indicating previous glacier extent. (Source: Dr. Dan McCarthy, Brock University & Mas Matsushita, Parks Canada.)

OBSERVED CHANGES IN RESERVOIR INFLOWS

Researchers have reconstructed streamflows for the Peace River at the Peace-Athabasca Delta using lake sediments, while others have used patterns of tree rings to establish long-term streamflow records for the Chilko River and its glacier-fed watershed in the Coast Mountains. Findings of these studies and of a similar study for the Columbia River at The Dalles indicate that over the past ~250 years both wetter and drier conditions than currently observed have persisted for decades under natural climate variability.

A detailed analysis of climate change signals in BC Hydro reservoir inflows found no significant trends of declining annual total water supply between 1984 and 2007. Rather, there is some evidence for a modest historical increase in streamflow in some basins. There is, however, clear evidence for changes in the seasonality of flow. Fall and winter flows have increased at most of BC Hydro's watersheds. There is weaker evidence for a decline in late-summer flows in snowmelt dominated watersheds. The absence of detectable trends in annual water supply does not imply that there are none, however. Brief record length and poor data quality mean a genuine but weak climate change signal could be hidden by more dramatic year-to-year fluctuations.

Climate patterns for the 21st century are derived from model simulations based on different emission scenarios. Emissions are difficult to project because they depend on economic growth, population increase, and technological and land-use changes, all of which are impossible to anticipate accurately. The emissions scenarios are designed to reflect the range of these uncertainties. Unless stated otherwise, results for all future scenarios focus on projections for the 2050s.

TEMPERATURE AND PRECIPITATION PROJECTIONS

In general, trends observed during the past century in British Columbia will likely continue throughout the 21st century. By the 2050s, all parts of British Columbia will very likely get warmer in all four seasons. The mean annual temperature is projected to increase by 1.4 to 3.7°C, which is greater than the range of historical variability. In the southeast, warming will be greatest in summer, while in the northeast, warming will be greatest in winter. In the Campbell River watershed and other parts of south coastal B.C., the warming will be more evenly distributed throughout the year.

Much of British Columbia will likely get modestly wetter (Figure 7) by 0 to 18 per cent. Contrary to temperature projections, however, the projected increase in precipitation is within the range of historical variability. Precipitation increases are projected to be greatest in fall, winter, and spring.

Precipitation increases are higher for the northern and northeastern parts of the province, where they are also more evenly distributed across all seasons. In summer, the southern portion of the province, and particularly the southwest, will likely become drier.

Median Precipitation Change Projected for the 2050s

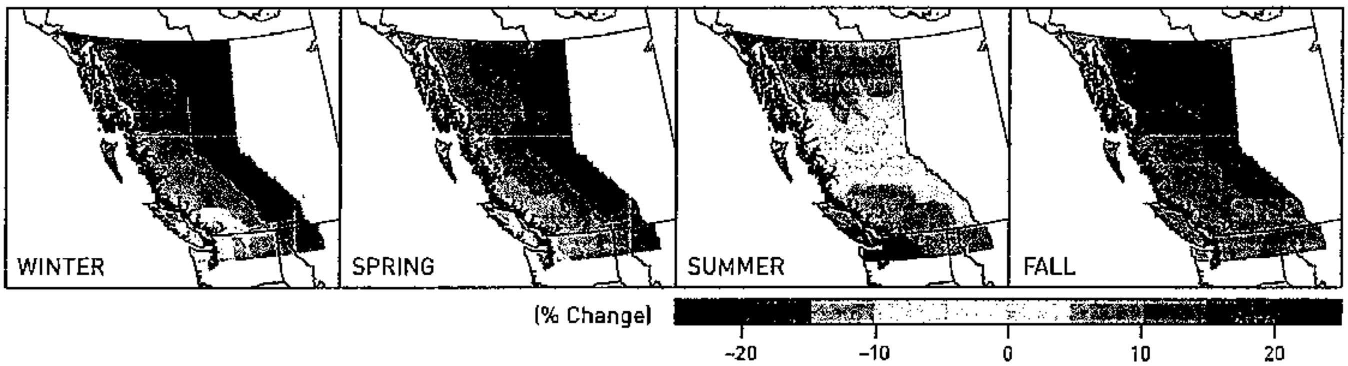


Figure 7: Seasonal mean precipitation change in the 2050s (2041-2070) relative to the 1961-1990 baseline period. (Source: Schnorbus et al. (2011)).

By 2050, the mean annual temperature in British Columbia is projected to increase by 1.4 to 3.7°C, which is greater than the range of historical variability.

HYDROLOGICAL PROJECTIONS FOR THE UPPER COLUMBIA REGION

Mica Dam drains 20,742 km² of the Columbia River headwaters. Annual precipitation averages 1,075 millimetres with 70 per cent falling as snow. The average annual temperature is 1.9°C. In 1985, glaciers covered 1,268 km², representing 6.1 per cent of the basin. Between 1985 and 2005, the glacier area shrank by 181 km², reducing glacier cover to 5.2 per cent of the basin.

GLACIERS

Glaciers in the Columbia basin are shrinking and, even with no further warming, would likely continue to retreat for at least another decade. Future simulations project that glacial coverage in the Mica basin will decrease by at least 44 per cent and possibly as much as 100 per cent by 2100, with an average decrease of 85 per cent. Figure 8 visualizes the retreat of the Athabasca glacier in the 21st century.

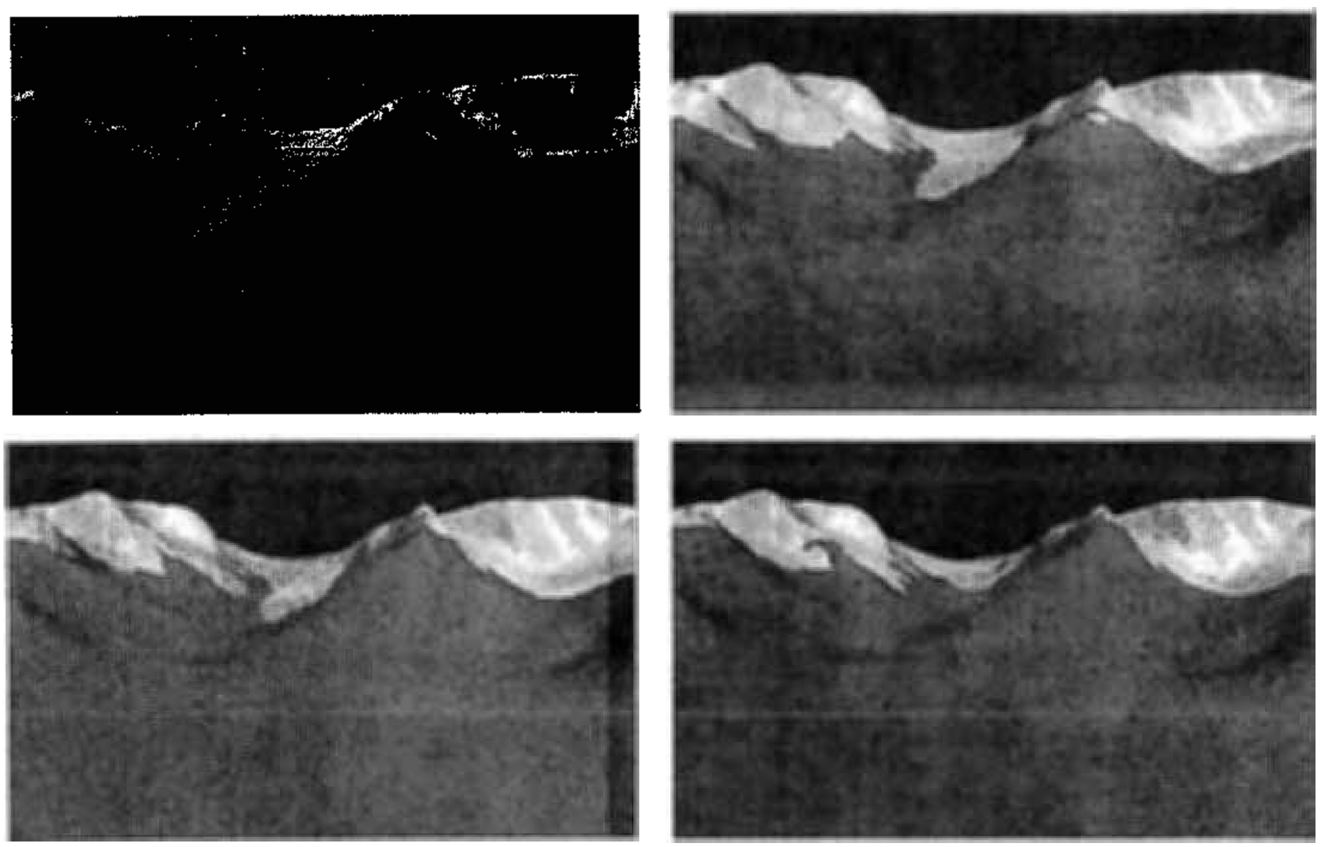
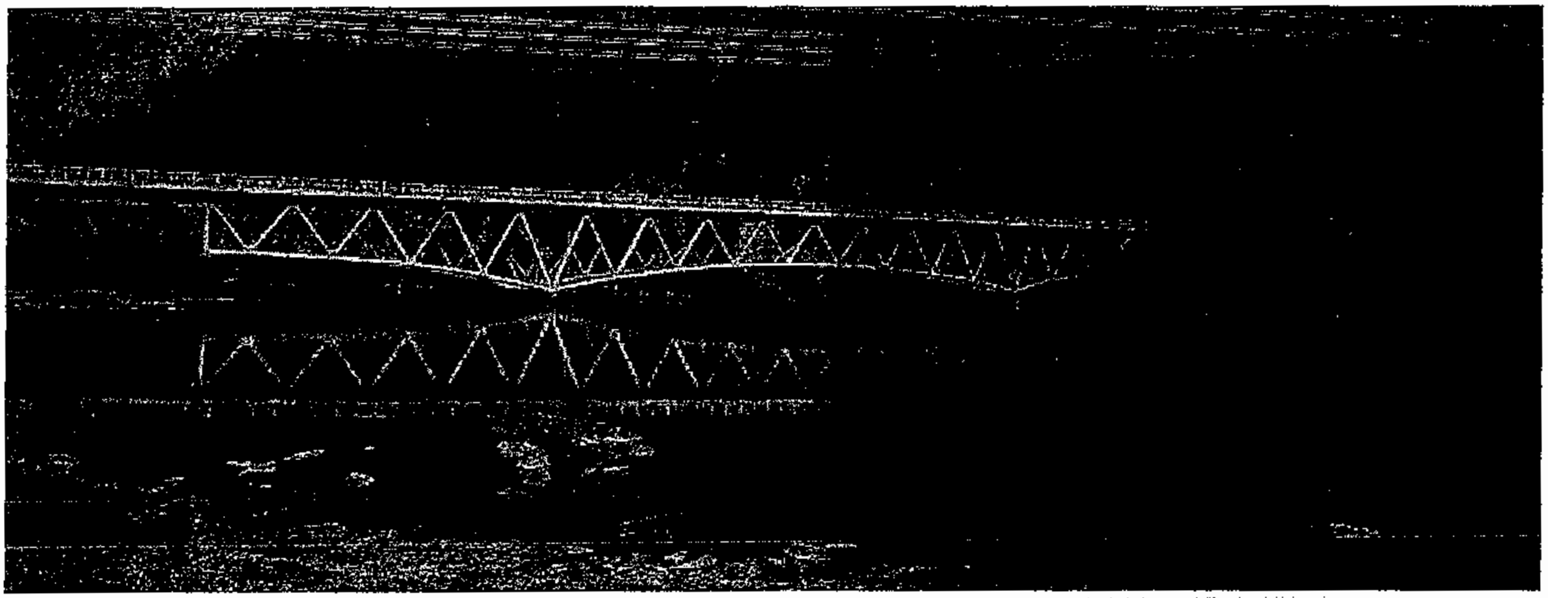


Figure 8: Athabasca Glacier coverage observed in 2001 (upper left, LandSat satellite photo) and projected for 2050, 2080 and 2100. GCM forced with the A1B emission scenario. Graphics: Glacier Modelling Group, Earth & Ocean Sciences, UBC.



STREAMFLOW PROJECTIONS

Streamflow projections for the Mica basin are available from three different studies [PCIC, WC2N, UW-CIG]. While streamflow projections for the Mica basin come with high levels of uncertainty, all three studies agree that the mean annual flow will increase (Figure 9). Each foresees an earlier onset of spring melt and lower flows in late summer and early autumn (Figure 10), consistent with other studies of streamflow in snow-dominated catchments. The decrease in icemelt contributions to August streamflow exacerbates the low flows in late summer produced by an earlier snowmelt. The overlap between the different emission scenarios (Figure 9b) shows that the primary source of uncertainty comes from modeling climate and hydrology rather than from GHG emission scenarios.

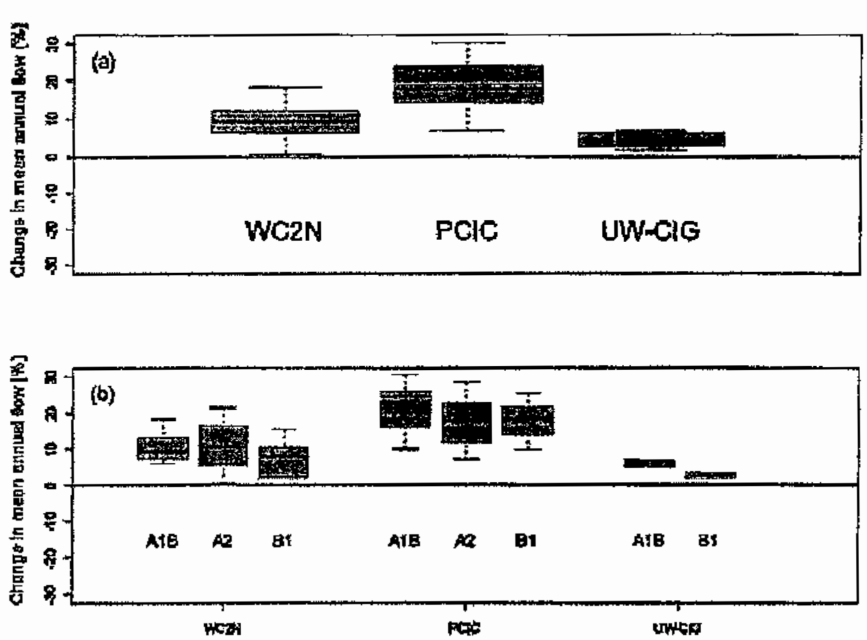


Figure 9: Projected changes in mean annual flow summarized for each study using (a) all studied emission scenarios and GCMs and (b) for each individual emission scenario.

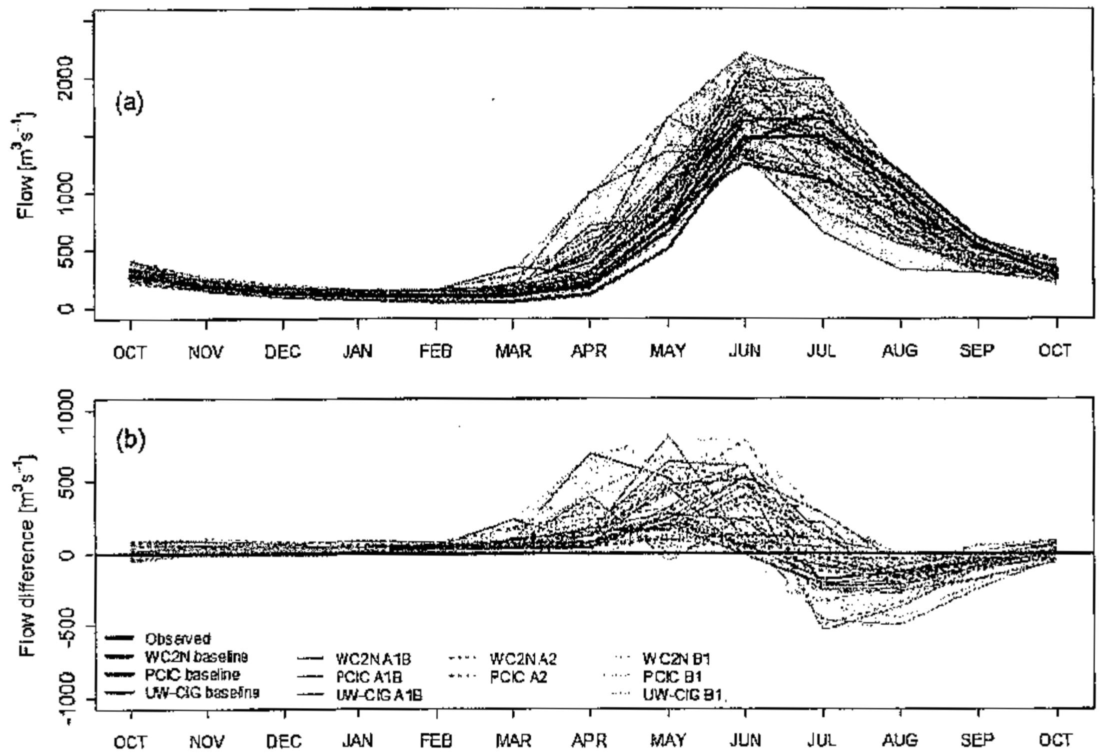


Figure 10: (a) Observed and future 2050s monthly Mica inflow and (b) flow anomalies relative to historical baseline for each study (bold lines) for all emission scenarios. Lines correspond to monthly medians for individual GCM runs under A1B, A2, or B1 emission scenarios. Flow anomalies (b) are plotted relative to the median of all historic runs for WC2N, PCIC and UW-CIG, respectively.

HYDROLOGICAL PROJECTIONS FOR THE PEACE REGION

The Williston basin in the northern Interior forms the headwaters of the Peace River. The region has a continental climate with frequent outbreaks of Arctic air. The mean annual precipitation is 838 millimetres, approximately 40 per cent in the form of snow. The average annual temperature is 0.2°C. A spring freshet is the dominant runoff event. Most precipitation falls as rain in the summer months, and glacier melt is negligible.

STREAMFLOW PROJECTIONS

Climate change scenarios for the Williston reservoir project an increase in inflow ranging between 11 per cent and 15 per cent by the 2050s, with streamflow increasing throughout most of the fall, winter and spring seasons (Figure 11). There is evidence for an earlier freshet onset and a shift in the peak flow from June to May. Summer flows are projected to decline, with the greatest decline in July.

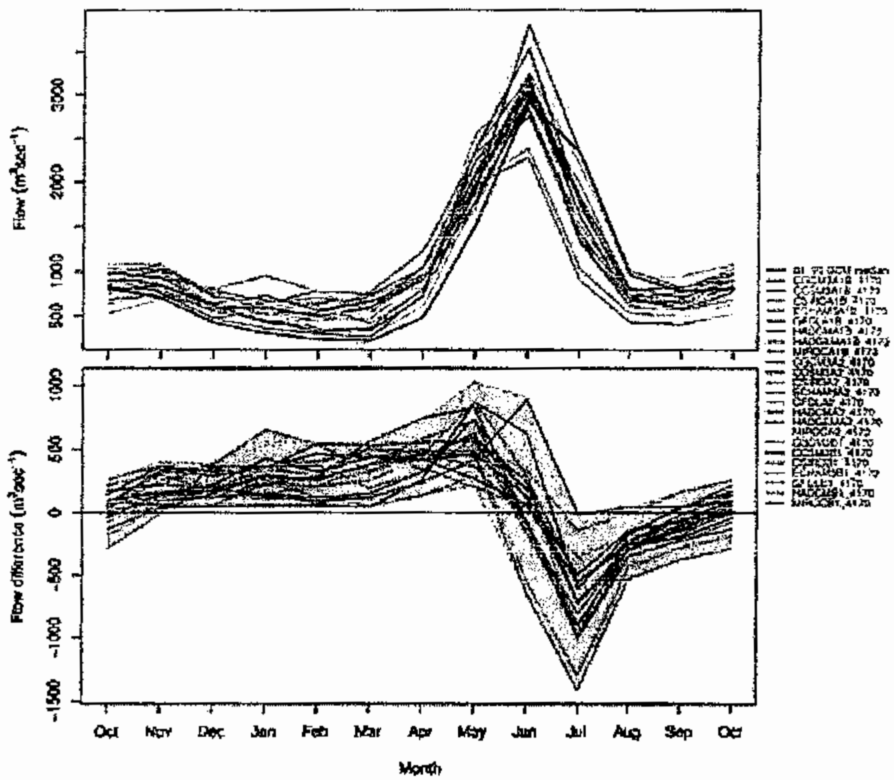


Figure 11: (a) Observed and future 2050s monthly Williston basin (GMS) inflow and (b) flow anomalies relative to historical baseline for each study (bold lines). The historic baseline is the median of all historic runs. Future streamflow is shown as the monthly median for each individual GCM/emission scenario combination. (Source: PCIC (Schnorbus et al. 2011)).

HYDROLOGICAL PROJECTIONS FOR VANCOUVER ISLAND, THE LOWER MAINLAND AND THE SOUTH COAST

Campbell River at Strathcona is a small coastal watershed that drains the central Vancouver Island mountains to the Strait of Georgia and impounds the Upper Campbell Lake and Buttle Lake Reservoirs. Annual precipitation in the study area is 2,960 millimetres, with 78 per cent falling from October to March. Inflows peak in the fall from rainfall and in spring from snowmelt, while glacier melt is negligible.

STREAMFLOW PROJECTIONS

By 2050, the Campbell River at Strathcona watershed is expected to change from a hybrid to a rainfall-dominated regime (Figure 12). Snowfall will decrease, and flows from October to April will increase, with a substantially reduced spring freshet. GCMs consistently predict the highest flow increases in January and the largest decreases in June. No significant changes to annual inflow volumes are projected.

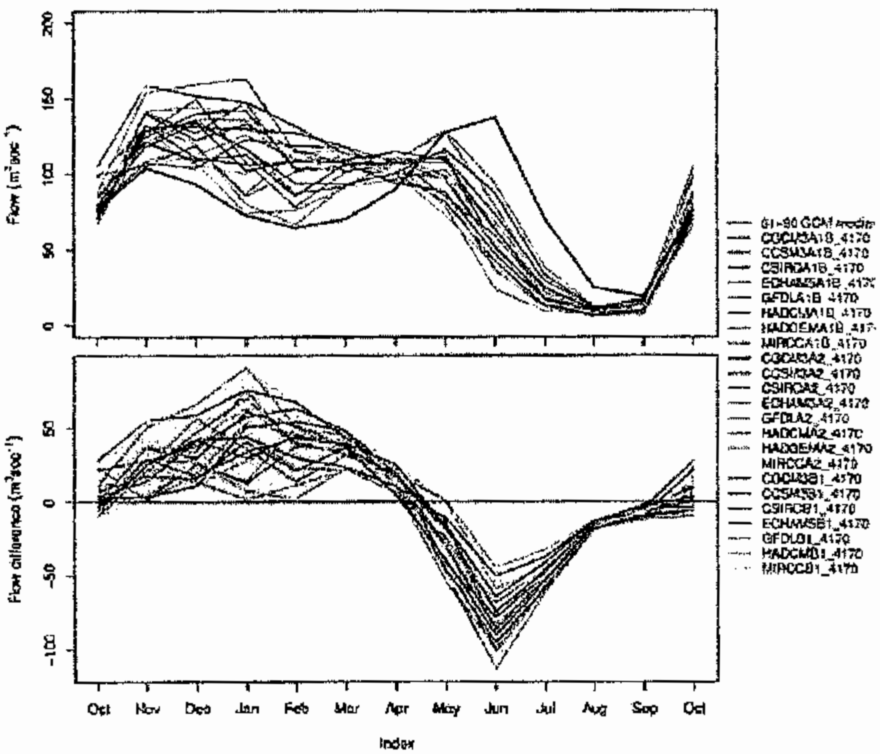
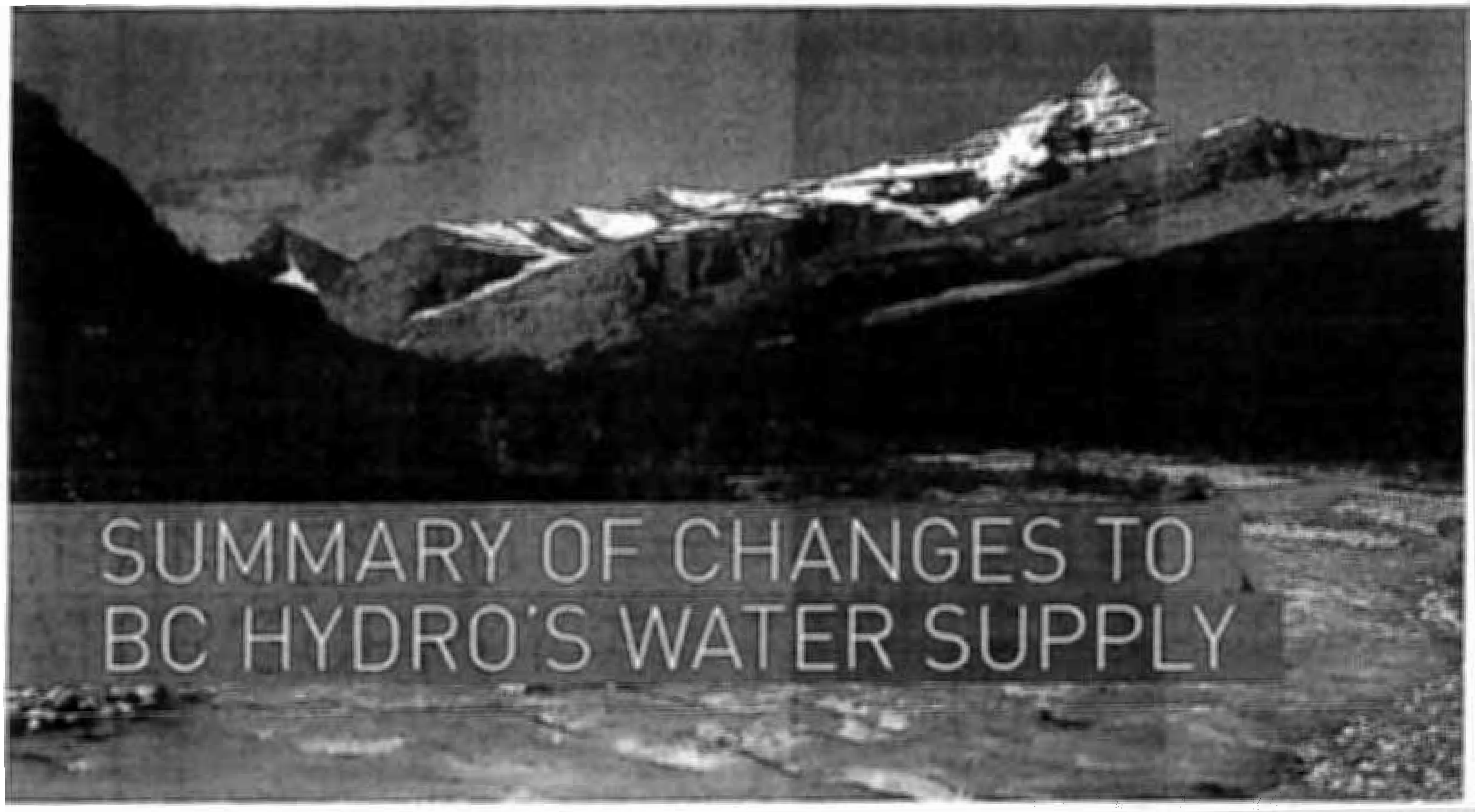


Figure 12: (a) Observed and future 2050s monthly inflow into Campbell River at Strathcona Dam and (b) flow anomalies relative to historical baseline for each study (bold lines). The historic baseline is the median of all historic runs. Future streamflow is shown as the monthly median for each individual GCM/emission scenario combination. (Source: PCIC (Schnorbus et al., 2011)).



SUMMARY OF CHANGES TO BC HYDRO'S WATER SUPPLY

ANNUAL CHANGES

Climate change projections for several of BC Hydro's watersheds suggest a likely small increase in water availability caused by a modest increase in future precipitation. Model uncertainties outweigh the relatively minor differences in projections among various emission scenarios.

There are regional differences in projections of future water availability. For the Mica basin, increases in overall water supply are likely, despite a decline in the glacier melt contribution, because increases in future precipitation more than offset the losses from shrinking glaciers (Table 2). Some models project an increase of only 10 per cent, others as much as 26 per cent. The Revelstoke and Arrow watersheds can also expect modest increases in annual flows. For the southern parts of the Columbia and Kootenay River basins (i.e., Whatshan, Kootenay Lake and Slocan) annual water supply is likely to slightly increase or remain unchanged. For the Williston basin, some GCMs see no change in water availability, while others predict increases of up to 15 per cent. The median projection is an increase of about 11 per cent. No significant changes to annual flows are projected for coastal watersheds.

All models have difficulties in simulating evaporation and the response of vegetation. However, potential and actual evaporation will likely increase due to higher temperatures, partly offsetting higher precipitation input. A notable exception is one model projected a decrease in evaporation for the Mica basin, which could further increase the annual water supply.

Table 2: Projected seasonal and annual inflow anomalies for select BC Hydro watersheds for the 2050s relative to 1961-1990 average under different emission scenarios. The anomalies refer to the median of the GCM ensemble for each emission scenario (Source: PCIC).

REGION	WATERSHED	EMISSION SCENARIO	WINTER	SPRING	SUMMER	FALL	YEAR
SOUTH COAST	Strathcona	A1B	51%	6%	-62%	11%	0%
		A2	43%	4%	-56%	7%	-2%
		B1	45%	9%	-47%	8%	4%
COLUMBIA	Mica	A1B	63%	79%	10%	11%	21%
		A2	75%	75%	9%	5%	17%
		B1	49%	53%	10%	7%	19%
	Revelstoke	A1B	107%	77%	-1%	10%	17%
		A2	124%	68%	-2%	1%	11%
		B1	77%	53%	5%	6%	15%
	Arrow	A1B	95%	61%	0%	-12%	10%
		A2	92%	61%	0%	-11%	4%
		B1	98%	57%	5%	-10%	10%
	Whatshan	A1B	117%	37%	-42%	5%	2%
		A2	114%	32%	-39%	-4%	-3%
		B1	84%	29%	-28%	6%	4%
KOOTENAYS	Duncan	A1B	49%	72%	7%	9%	16%
		A2	58%	73%	5%	5%	12%
		B1	43%	49%	10%	7%	15%
	Kootenay Lake	A1B	95%	44%	-17%	-5%	8%
		A2	84%	35%	-15%	-10%	3%
		B1	79%	32%	-5%	1%	10%
PEACE	Williston	A1B	84%	61%	-17%	8%	12%
		A2	64%	60%	-16%	5%	9%
		B1	56%	46%	-12%	5%	13%

Key: little or no change: -5% and 5% increase: > 5% decrease: < -5%

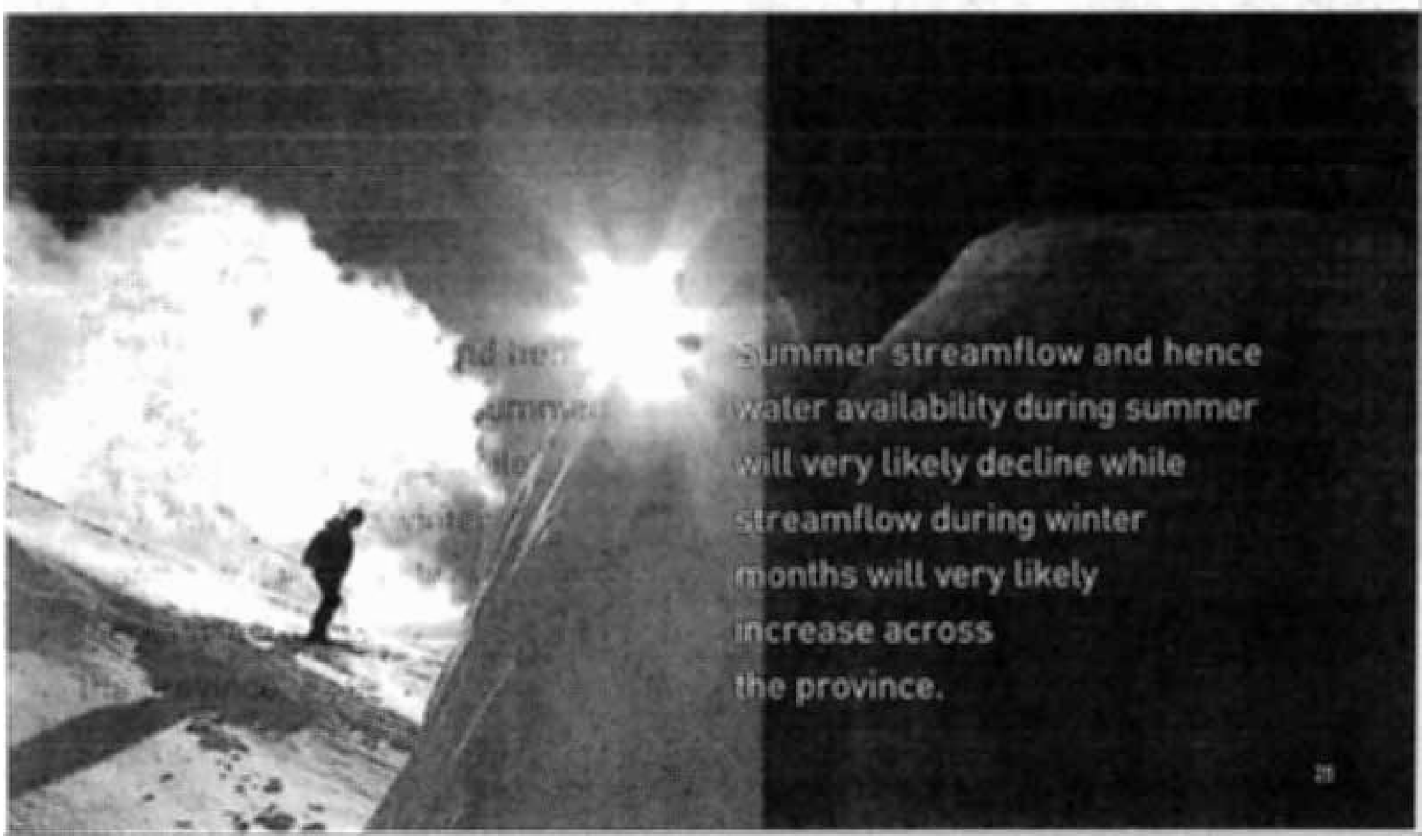
A modest increase in future annual water availability is likely for BC Hydro's integrated hydroelectric system.

SEASONAL CHANGES

Summer streamflow and hence water availability during summer will very likely decline across the province. Snowmelt will start earlier and flows will peak earlier. This has already been observed over the past few decades. Snowmelt-dominated watersheds in southeastern B.C., for example Arrow and Kootenay Lakes, will experience higher flows during winter and lower flows during late summer, but will very likely remain snowmelt-dominated. The Williston basin will remain a hybrid snowmelt- and rainfall-dominated watershed.

Glaciers are projected to continue retreating under all future climate scenarios. Under a warming climate, the contribution of glacier melt to streamflow initially increases but eventually declines as glaciers shrink. Evidence shows that B.C. glaciers are already shrinking and studies suggest that the glacier melt contribution to streamflow is already declining. In the Mica basin, approximately 60 per cent of glacier cover is projected to disappear by 2050 and 85 per cent by 2100. Some scenarios show a complete loss of glaciers in the region by 2100.

The biggest changes to seasonal flow regimes can be expected for coastal watersheds. There, rainfall-runoff processes will very likely become dominant over snowmelt. Hybrid rainfall- and snowmelt-dominated watersheds will turn into rainfall-dominated watersheds. With only marginal precipitation increases, the region will see a decline of basin-wide snowpack and consequently a reduction in spring runoff.



NEXT STEPS

Climate change impact studies give a reasonably good understanding of future trends in water availability, but have only been undertaken for some BC Hydro watersheds. BC Hydro has renewed its partnership with the Pacific Climate Impacts Consortium to expand the hydrologic impact studies to other BC Hydro watersheds.

The next step for BC Hydro is to feed operational and planning models with projected inflow scenarios to assess how sensitive hydroelectric power generation is to climate change. For instance, it has not been determined how effectively reservoir storage will be able to buffer projected changes in seasonal runoff timing, such as lower summer inflows. Changes in the year-to-year variability of water supply, and hence changes to the frequency and severity of hydroelectric droughts will also need further research.

Water availability is but one of many climate-related factors affecting hydroelectric power generation. Just as important are the effects of a changing climate on heating and cooling demand, on infrastructure such as transmission and distribution lines, impacts to fisheries and habitat, as well as changes in demographics, socio-economics, and government policies and regulation. All these factors must be integrated to develop a useful and holistic vision of how best to adapt to a changing climate. To this end, BC Hydro continues to work with the Pacific Climate Impacts Consortium and others to expand our knowledge of climate change science. An Adaptation Working Group at BC Hydro continues to assess and address the risks of climate change, and to continue powering B.C. with clean, reliable electricity, for Generations.

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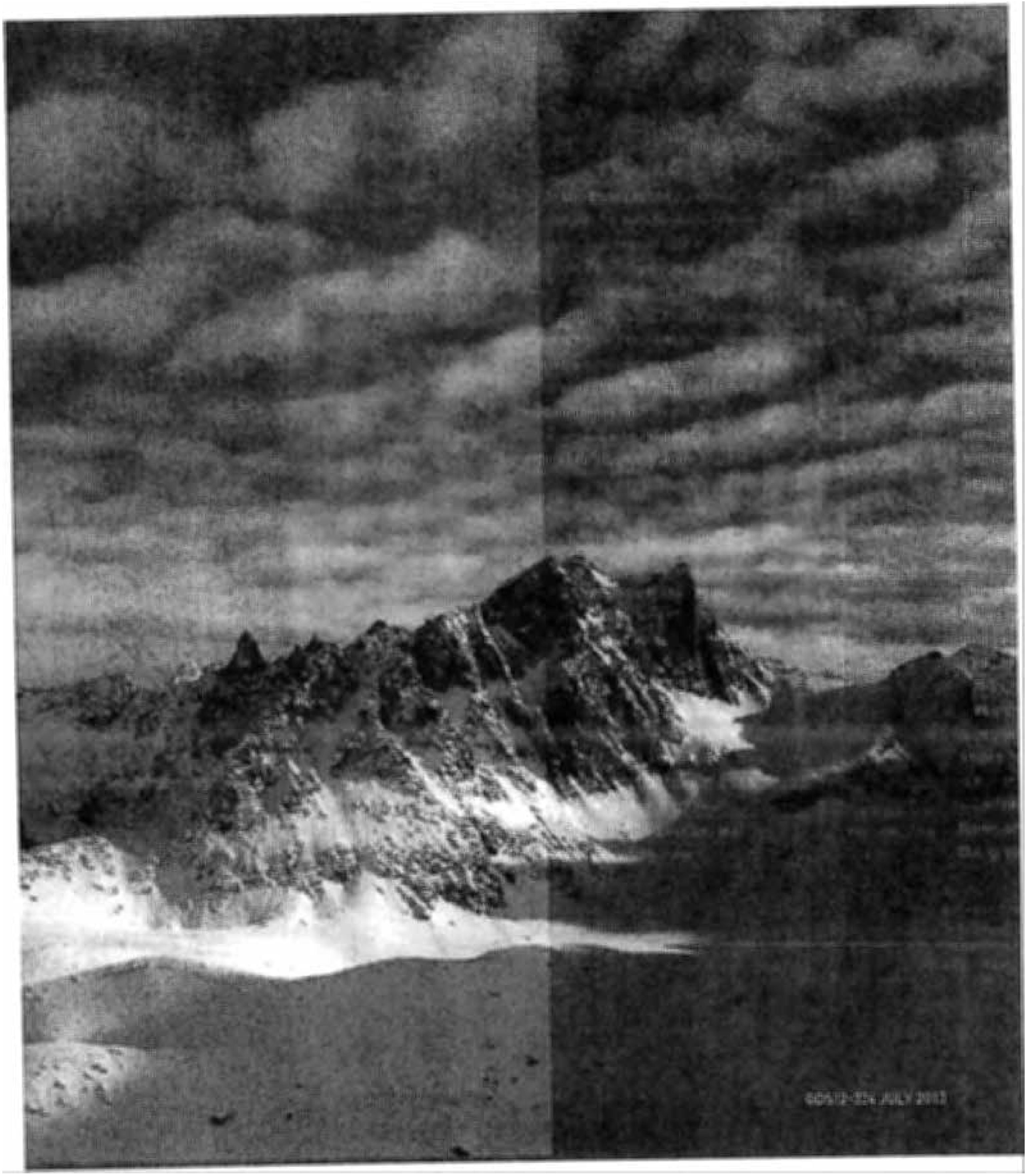

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of Tim Leslie #2
sworn before me this 15th day
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British Columbia's Revenue-Neutral Carbon Tax: A Review of the Latest "Grand Experiment" in Environmental Policy

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CONTENTS

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SUMMARY

In 2008, British Columbia implemented the first comprehensive and substantial carbon tax in North America. By 2012, the tax had reached a level of C$30/t CO2, and covered approximately three-quarters of all greenhouse gas emissions in the province. This paper reviews existing evidence on the effect of the tax on greenhouse emissions, the economy, and income distribution as well as provides new evidence on public perceptions of the tax.

Empirical and simulation models suggest that the tax has reduced emissions in the province by 5–15%. At the same time, models show that the tax has had negligible effects on aggregate economic performance, though certain emissions-intensive sectors have faced challenges. Studies differ on the effects of the policy on income distribution but agree that they are relatively small. Finally, polling data show that the public initially opposed the tax but now generally supports it.

The carbon tax was originally implemented as a "textbook" policy, with wide coverage, few exemptions, and use of revenue for low-income tax credits and broad-based tax cuts. But the recent use of some tax revenues to support particular industries rather than to deliver those broad-based tax cuts may reduce its overall cost-effectiveness.

Introduction

In a 1998 article in the *Journal of Economic Perspectives*, "What Can We Learn from the Grand Policy Experiment?" Robert Stavins examined the performance of the SO_2 allowance ("acid rain") trading program in the United States in its first several years (Stavins 1998). Stavins' interest was motivated by the fact that the SO_2 trading program was by far the world's most ambitious application of emissions trading, representing a textbook policy approach that economists had been prescribing for decades as an alternative to "command-and-control" regulation, yet it had little uptake from environmental regulators. Stavins examined the policy's application from several angles, providing insights into its cost-effectiveness, the political economy forces that led to its selection, and normative prescriptions for policy design.[1]

In the economist's environmental policy playbook, nothing competes with emissions permit trading for space more than environmental taxation (Weitzman 1974). And no contemporary environmental issue has emphasized the choice between these two instruments more than climate change (Goulder and Schein 2013). Putting a price on carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions has long been the foundation of economists' prescription for the climate change problem. And regulators have taken notice. Carbon-pricing has firmly taken root over the last decade; mandatory pricing systems (existing or planned) are found on every continent except Antarctica (World Bank 2014). From an emissions coverage standpoint, emissions trading systems (ETS), or *cap-and-trade* programs, are the most prevalent carbon-pricing approach. Some of the historic preference for an ETS over a tax may be due to the political economy factors referenced by Stavins (1998) and addressed through a political science lens by Paterson (2012), but an exploration of the reasoning behind those choices is beyond the scope of this paper.

Although ETS predominates in climate policy, several jurisdictions either have or are considering a tax alone or in combination with an ETS. Some countries (e.g., Sweden) have had a carbon tax since the 1990s, and Ireland and other European Union (EU) countries have recently implemented them, but these tax systems have often been part of larger energy and excise tax reform efforts rather than focused on GHG emissions. Those European tax systems also have different scopes of coverage and rates and are coupled with the EU ETS. Thus it is difficult to assess the effectiveness of the tax in isolation.

In contrast, the Canadian province of British Columbia (BC) instituted in 2008 a stand-alone carbon tax that covered about three-quarters of all emissions sources in the province at a levy rate that was as high as or higher than carbon prices emerging from ETS throughout the world. Among the unique elements of the BC carbon tax is its goal of *revenue-neutrality*, meaning that all revenues raised by the tax are to be recycled to BC households and businesses, largely in the form of tax cuts. As discussed below, economists often favor revenue-neutral carbon taxation because it has the potential to enhance economic growth by lowering distortions from the current tax system. As such, it may provide the purest example of the economist's carbon tax prescription in practice. Thus the BC carbon tax can be viewed as another grand policy experiment—much as Stavins viewed SO_2 allowance trading in the 1990s—that we can now assess for effectiveness in achieving environmental, economic, and political objectives.

The BC carbon tax's effect on emissions, economic indicators, and political acceptance has been the subject of some targeted empirical work. However, no papers have broadly gauged its performance across the policy's multiple outcomes of interest. This paper seeks to do that by drawing from the small but

[1] Fifteen years later, Stavins and Richard Schmalensee revisited the grand policy experiment in the pages of the same journal, highlighting what they referred to as an "ironic" history of the policy, including policy design choices that "worked" despite their flaws, rejection of emissions trading by some of the political constituencies that initially argued on its behalf, and a massive change in the regulation underlying the market that caused the market to collapse (Schmalensee and Stavins 2013).

growing empirical literature to distill evidence on the tax's effectiveness across many dimensions: emissions, economy, equity, and public acceptance.

The paper provides a brief history of the BC carbon tax, focusing on political and economic factors underlying its introduction and briefly summarizes its key design elements of the tax: coverage base, levy rate, and use of revenues. In addition, the paper reviews the studies that have estimated the effect of the tax on British Columbia's emissions profile and synthesizes the research on the tax's economic effects, exploring whether the tax has impeded or enhanced economic growth, given theoretical priors that it could go either way with judicious recycling of the revenues. The paper concludes with an exploration of the distributional consequences of these economic effects across the BC population, a review of the evidence on public acceptance of the tax, and a summary of findings.

History of the Tax

The BC carbon tax was implemented on July 1, 2008. It was borne of a unique confluence of social, political, and economic forces. Public concern over climate change risks surged in Canada and elsewhere during the first decade of the 21st century as a result of mounting scientific evidence of human influence on the climate system (IPCC 2007), increased attention in the press and in popular culture to climate change with a call for political action (Gore 2006), and emerging expectations that all major emitting countries were poised to take serious action to reduce GHG emissions under the United Nations Framework Convention on Climate Change (UNFCCC). These concerns and expectations were coupled with the evolution of carbon-pricing mechanisms as the recommended policy instrument to address climate change.

These factors driving global action coincided with five developments in British Columbia that Harrison (2013) attributes to passage of the BC carbon tax: (1) the prevalence of hydro power as the source of electricity generation; (2) intense voter interest in the issue of climate change from an electorate with strong environmental views; (3) the presence of a right-center majority government with bona fide support in the business community that could perhaps push an environmental agenda further than a government considered hostile to business interests; (4) strong commitment by BC Premier Gordon Campbell, who essentially staked his political career on passage of the carbon tax; and (5) a political institutional structure that gives great power to the leader of the party that holds a majority of seats in the legislature, as was the case with Campbell and his party.

Even with this favorable combination of factors, passage of the tax was not easy. To capture the support of the business community, the tax was made revenue-neutral—that is, revenues would be countered by tax cuts elsewhere—and was applied to both businesses and households (Harrison 2013). These features created political backlash in some corners due to concern that low-income and rural (especially northern) communities would be unfairly burdened (Beck, Rivers, and Yonezawa 2015). Ultimately, the tax was designed to direct some of the proceeds as payments and tax reductions for northern rural households and low-income groups.

Some observers viewed the 2009 provincial election as a referendum on the BC carbon tax, and the opposition party called for its abolition as part of an "Axe the Tax" campaign.[2] However, the state of the economy in the midst of the global recession was foremost in voters' minds, and voters viewed the ruling party more favorably than the opposition on economic issues (Harrison 2013). Perhaps for this reason, more than the carbon tax itself, the ruling party survived the 2009 election, as did the carbon tax.

[2] The opposition party in British Columbia at the time was the New Democratic Party or NDP, generally regarded as a left-center party. The party in power was the Liberal Party, which is regarded as representing right-center interests.

The BC government is entitled to review the progress of the carbon tax toward its stated goals, and it chose to do so as part of its 2012–13 annual budget process (BC Ministry of Finance 2013). The review covered key aspects of the carbon tax, including revenue neutrality, and the impact of the tax on the competitiveness of BC businesses. The review largely confirmed that the tax was achieving its goals and recommended no major changes to the program.

Key Design Features

Table 1 summarizes the key provisions of the BC carbon tax. As the first comprehensive carbon tax in North America, it is relatively simple in its design and application.

Table 1. Key provisions of British Columbia carbon tax

Provisions	Description
GHG emission sources covered	Fossil fuels used within the province, accounting for 70-75% of all GHG emissions in the province. Greenhouse gases are converted to carbon dioxide equivalents using 100-year global warming potentials.
Notable exemptions	• Fuels exported from BC • Fuel use by planes and ships travelling to or from BC • Greenhouse operations and fuel used in agriculture (starting in 2012 and 2013, respectively) • All non-fossil fuel GHG emissions including those from industrial processes, landfills, forestry and agriculture. • Fugitive emissions of methane (CH_4) from production and transmission of fossil fuels.
Tax rate	Started at C$10/ton CO_2 in 2008, rising to $30/ton by 2012. This tax per ton CO_2 is then transformed to the units of sale (e.g., $ per litre of gasoline) for assessment at the point of purchase. See Table 2 for respective tax rate per unit of the most common fuels.
Use of tax revenues	Tax aspires to revenue-neutrality, meaning all revenues are redistributed back to households in the form of tax reductions or directed transfers rather than used to increase government spending. Actual experience has revealed tax cuts and targeted payments in excess of the revenue raised by the carbon tax and some movement from general household and business tax reductions to expenditures targeted for specific purposes.
Transparency provisions	BC Ministry of Finance is required each year to prepare a three-year plan for recycling carbon tax revenues through tax reductions. The plan is presented to the Legislative Assembly for review and approval.

Coverage

The tax covers GHG emissions resulting from the combustion of all fossil fuels used within the province, with some minor exceptions. The taxed fuels include liquid transportation fuels such as gasoline and diesel as well as natural gas or coal used to power electric plants, along with other types of fuels. It covers 70–75% of the province's GHG emissions; the uncovered remaining emissions include non-combustion CO_2 in industrial processes (e.g., lime production in cement manufacture), methane (CH_4) emissions from natural gas extraction and transmission, methane and nitrous oxide (N_2O) emissions from agriculture and CO_2 emissions from forestry (British Columbia Ministry of Finance 2015).

The tax as originally implemented offered no exemptions for particular sectors and used the same tax rate for all covered sectors, which distinguished it from other carbon-pricing efforts worldwide. However, in 2012, responding to concerns raised by greenhouse growers that the carbon tax was rendering their operations uncompetitive with California and Mexico, government offered a one-time exemption (worth $7.6 million) from the carbon tax. This exemption was followed in the 2013 budget with an ongoing 80% exemption for greenhouse growers. In the 2014 budget, government announced that gasoline and diesel used for agriculture would be exempt from the carbon tax (Rivers and Schaufele 2015).

Tax Rate: Absolute and Relative

The tax started at C$10 (Canadian dollar) per ton of carbon dioxide equivalent when introduced in 2008. It then rose C$5 per ton each year until in 2012 it reached C$30 per ton, at which it remains today. Because different fuels have different carbon contents, the tax rate per unit of fuel differs, as does the impact on final price, as shown for selected fuels in Table 2. The carbon tax translates to a set price per unit of fuel output rather than fixed percentage; however, it is useful to see how much the tax contributes to the final price of different fuels. The carbon tax accounts for a relatively modest share of the final price for gasoline, diesel, and propane, but it can account for a very large share of the price of natural gas and coal. The differences in relative price impact are due primarily to the fact that raw fossil fuel costs are a small portion of total retail fuel cost for refined fuels such as gasoline, diesel, and propane than they are of primary energy fuels such as coal and natural gas. These differences do suggest that the carbon tax has, for instance, a higher potential effect on coal and gas use than on transportation fuel use; however, virtually all of the coal mined in British Columbia is used elsewhere and is not subject to the BC carbon tax.

Table 2. Selected carbon tax rates by fuel

Fuel type	Tax unit	Tax rate (in 2015)	Tax % of final fuel price (2014)
Gasoline	C¢/liter	6.67	4.4%
Diesel (light fuel oil)	C¢/liter	7.67	5.1%
Natural Gas	C¢/cubic meter	5.7	33.9%
Propane	¢/liter	4.62	7.1%
Coal high-heat value	C$/ton	62.31	54.7%
Coal low-heat value	C$/ton	53.31	46.8%

Sources: For tax data—British Columbia Ministry of Finance (2015); for price data—Natural Resources Canada (2015) (gasoline and diesel for Vancouver, British Columbia), Natural Resources Canada (2014) (natural gas and propane for Canada), and British Columbia Ministry of Metals and Mines (2013) (coal).
Note: See http://www.sbr.gov.bc.ca/documents_library/bulletins/mft-ct_005.pdf for the full list of tax on all covered fuels.

To place the BC carbon tax in context, Table 3 compares it to carbon prices found in several other programs in North America and the European Union. To facilitate comparisons, prices are converted from their domestic currency and units into U.S. dollars (US$) per (metric) ton CO_2e. British Columbia has the highest price of the cohort, twice as high, for instance, as the carbon tax in France and the fee paid in Alberta for entities that exceed the emissions intensity target. The exceedance fee in Alberta, however, is only paid on the amount that the realized emissions rate exceeds the intensity target, whereas the BC carbon tax is paid on all covered emissions, so the carbon cost difference between British Columbia and Alberta is even more pronounced than Table 3 implies. All other carbon-pricing systems in Table 3 emanate from cap-and-trade programs, making the price comparison a bit more fluid. Whereas a carbon tax sets a fixed price, a cap-and-trade program sets a fixed emissions cap that is met by parties trading emissions allowance permits at a market price. This price will vary constantly in response to shifts in market demand for emissions allowances caused by macroeconomic, energy market, and policy shocks (Murray and Maniloff 2015).

Table 3. British Columbia carbon tax level compared to other carbon prices

Region	Program	Domestic price (2015)[a]	US$/ton[b]
British Columbia	Carbon tax	C$ 30/ton	24.00
Alberta	Emission intensity target (fee for exceedance)	C$ 15/ton	12.00
California-Quebec	Cap and trade (economywide)	US$12.21/ton[c]	12.21
Northeastern United States	Cap and trade (electric power sector)	US$ 5.41/short ton[d]	6.06
European Union	Cap and trade (economywide)	€ 6.80/ton[e]	7.34
France	Carbon tax on transport fuels and domestic heating fuels	€ 14.50/ton (rising to €22 in 2016)	15.66

[a] Nearest quote to April 8, 2015.
[b] Exchange rates between Canadian dollar and U.S. dollar (0.80) and the euro and U.S. dollar (1.08), quoted on April 8, 2015, XE Currency Converter (http://www.xe.com/currencyconverter/).
[c] U.S. Energy Information Administration. 2015. "California and Quebec Complete Second Joint Carbon Dioxide Emissions Allowance Auction." 2015. http://www.eia.gov/todayinenergy/detail.cfm?id=20312.
[d] RGGI Incorporated. 2015. *Market Monitor Report for Auction 27.* http://www.rggi.org/docs/Auctions/27/Auction_27_Market_Monitor_Report.pdf. Note: a short ton is equal to 2000 pounds, which is 0.9072 tons (metric ton).
[e] Bloomberg Professional Services data base. Downloaded April 14, 2015.

Use of Revenues

One key aspect of the BC carbon tax is its revenue neutrality. Rather than raise taxes and increase government expenditure, it operates as a tax shift, wherein carbon tax revenues are countered by cuts in other taxes or direct transfers to households. These shifts include business tax cuts, personal income tax cuts (targeted at lower-income categories), low-income tax credits, and direct grants to rural households.

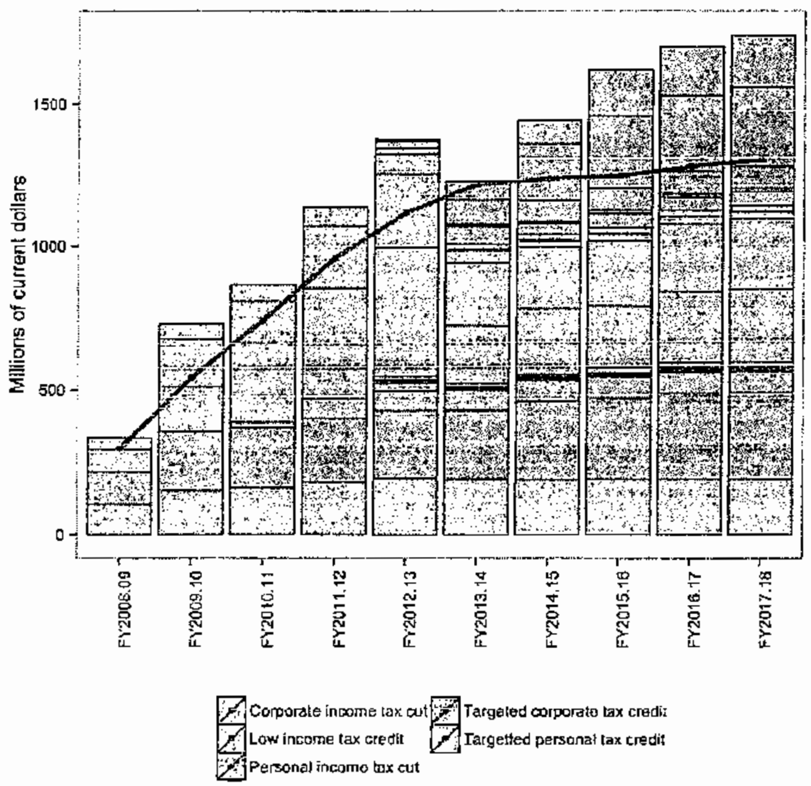
To address potential skepticism that the BC government might not follow up on promises to keep the tax revenue neutral, the BC Ministry of Finance must file a report each year showing how the tax proceeds are being used.[3] The report is subject to review and approval by the BC Legislative Assembly as part of the broad annual budget review process. Between its inception in 2008 and 2015, the BC carbon tax has generated C$6.1 billion in revenue, yet corresponding tax cuts have been more than C$7.1 billion. Thus the tax has not truly been revenue neutral to date, a point considered below. Slightly more than half the tax cuts have been directed to businesses and the remainder, to households.

Figure 1 illustrates the distribution of actual and planned uses of the carbon tax revenue from the tax's inception in Fiscal Year 2008–09 through 2017–18. From implementation to 2012, virtually all tax revenues were recycled through tax rate cuts and credits in personal and business tax rates, many targeting low-income households. Starting in 2012–13, when the tax rate reached its target rate of C$30 and revenues climbed accordingly, some of the revenue started to be targeted for specific business purposes. For example, in that year, a portion of the carbon tax revenue was directed to an "interactive

[3] A true assessment of revenue neutrality requires knowledge of what government would have done in the absence of the tax. It is possible, for example, that some of the tax cuts that were made concurrently with the tax would have been made even without implementation of the tax.

digital media tax credit." The dynamic began to change considerably from 2013–14 onward, first with certain exemptions (to greenhouse growers and then to the broader agricultural sector (Rivers and Schaufele (2015)), which slightly lowered the tax base, and a partial reversal of the corporate income tax rate cut, which reduced those broad business tax cuts as a use of revenues. After that point, virtually all the tax's revenue growth has been targeted to corporate tax credits in certain sectors, in particular the motion picture industry. What began as use of carbon tax revenues for general tax reform to reduce distortions and promote economic growth (straight out of the economist's playbook) appears to have evolved into a system with some "industrial policy" objectives of promoting certain sectors.

Figure 1. Distribution of uses of BC carbon tax revenues, 2008–2018



Source: BC Budget and Fiscal Plans, 2008–09 to 2015–16; www.gov.bc.ca/fin/.
Notes: The solid line represents revenue from the carbon tax; the bars represent expenditures of carbon tax revenue. Values for FY2015–16 and beyond are forecasts from the most recent budget.

Effect on BC Emissions

British Columbia's carbon tax was implemented with the aim of reducing GHG emissions. Determining the success of the policy in this regard requires comparing actual GHG emissions in the province after the policy was implemented with a counterfactual scenario estimating emissions in the province in the absence of the tax. As with other evaluation studies, constructing the counterfactual scenario is the key to successfully identifying the effect of the policy. Empirical studies of the carbon tax have taken either a numerical simulation modeling approach or an econometric approach (Table 4).

In the former approach, models (e.g. computable general equilibrium) are simulated with and without the carbon tax, and the effect of the carbon tax is the difference in these two scenarios. The challenge with this approach is that the models require a large number of functional form and parametric assumptions. Moreover, these assumptions are typically not validated against empirical data.

When the literature takes an econometric approach, it typically uses a difference-in-difference approach by comparing British Columbia before and after implementation of the tax and to other provinces. The challenge with econometric studies is accounting for unobserved variables that are correlated with the tax. These variables include other policies or economic conditions.

Table 4. Summary of studies that estimate the effect of British Columbia's carbon tax on GHG emissions and fuel consumption

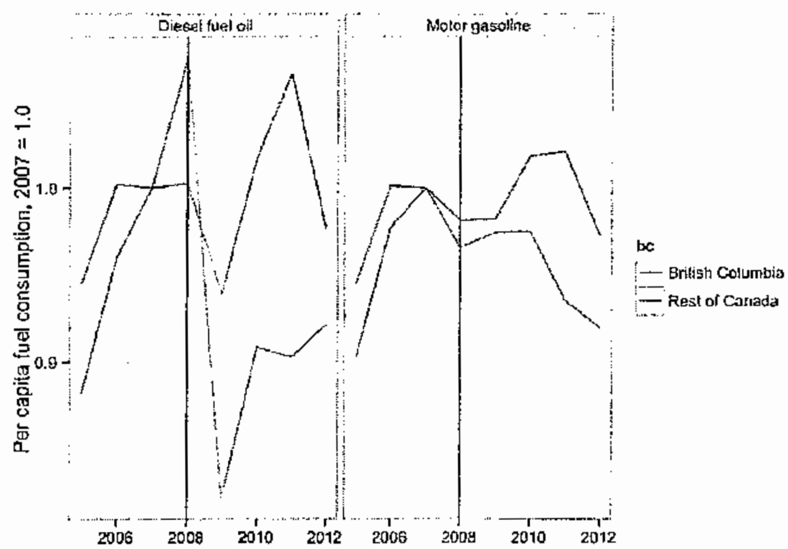
Source	Method	Results
British Columbia (2008)	Numerical simulation model with technological detail	5% reduction in GHG emissions
Beck et al. (2015)	Computable general equilibrium model	8.5% reduction in GHG gas emissions
Elgie and McClay (2013)	Difference-in-difference with no additional controls	18.8% reduction in per capita sales of petroleum fuels subject to the tax
Elgie and McClay (2013)	Difference-in-difference with no additional controls	9% reduction in per capita GHG emissions (data to 2011 only)
Rivers and Schaufele (2012)	Difference-in-difference with controls	11–17% reduction in per capita gasoline sales
Gulati and Gholami (2015)	Difference-in-difference with controls	15% reduction in residential natural gas demand; 67% reduction in commercial natural gas demand
Bernard, Guenther, and Kichian (2014)	Time series analysis	7% reduction in per capita gasoline sales

In the original Climate Action Plan that accompanied introduction of the tax, modeling work using the CIMS energy-economy model suggested that the tax would reduce GHG emissions by about 3 Mt CO_2 annually by the year 2020 in the absence of any other policies (British Columbia 2008, 20), or by roughly 5% compared to the reference case (counterfactual) forecast.

Beck et al. (2015) conduct a similar analysis using a computable general equilibrium model and estimate that the tax is likely to reduce GHG emissions by 8.5% relative to the counterfactual scenario.

Recent work uses data on fuel consumption and GHG emissions from after the tax's introduction to estimate the effect of the tax on emissions. Most studies use a difference-in-difference approach, comparing fuel sales in British Columbia to those in other provinces, and comparing periods before and after the tax's introduction, as in Figure 2. Elgie and McClay (2013) conduct such a study, comparing trends before and after the tax's introduction in British Columbia and other provinces. They find roughly a 19% reduction in per capita sales of fuels subject to the tax over the 2008–2012 period relative to fuel sales in other Canadian provinces. Importantly, they find that for fuels not subject to the carbon tax, such as aviation fuel, there was no emissions reduction. In the same study, they use a different data set on aggregate GHG emissions and find a 9% reduction in per capita GHG emissions. Notably, their analysis does not control for any other factors affecting petroleum sales, so although their analysis is suggestive of a strong effect from the tax, it is not possible to interpret that effect as causal evidence.

Figure 2. Trends in gasoline and diesel fuel oil sales in British Columbia and the rest of Canada, 2005–2012



Source: Data from Statistics Canada, Tables 134-0004 and 0051-0001.
Note: The vertical black line indicates introduction of the carbon tax.

Rivers and Schaufele (2012) estimate the effect of the BC carbon tax on gasoline sales. They conduct a difference-in-difference-type analysis as above but include controls for other covariates that could affect gasoline sales, such as income, prices, the business cycle, and public transit investments. Their coefficients suggest that at \$30/t CO2, the carbon tax caused a reduction of 11–17% in gasoline sales. They note that this effect is much larger than would be expected if consumers responded to the carbon tax in the same way that they responded to other changes in gasoline price.

Gulati and Gholami (2015) analyze residential and commercial natural gas sales using a similar difference-in-difference approach. Like Rivers and Schaufele (2012), they find that the carbon tax appears to have reduced commercial natural gas consumption by a larger amount than would be expected on the basis of the normal response to changing commercial natural gas prices. In the case of residential natural gas consumption, however, they find no such amplified response to the tax relative to the natural gas price; for residential consumption, their estimates suggest that the carbon tax likely reduced consumption by about 15%.

Bernard, Guenther, and Kichian (2014) conduct a time series analysis of the effect of the carbon tax on gasoline sales in British Columbia, using monthly data on sales, excise taxes, the carbon tax, and gasoline price. They find that both carbon taxes and excise taxes cause a much larger reduction in gasoline sales than other price movements, and overall they estimate a reduction in per capita gasoline sales due to the carbon tax of some 7%.

The estimates reported in Table 4 use quite different methods but reflect overall effects that are of roughly the same magnitude, providing analysts with some confidence in them. On the basis of these results, it is reasonable to claim that the effect of the tax was to reduce fuel consumption and GHG emissions 5–15% in British Columbia.

Effect on the BC Economy

A carbon tax will induce taxed parties to reduce emissions up to the point that the marginal cost of the reduction just equals the tax. If the tax is set commensurately with the marginal benefit from emissions reduction, an economically efficient outcome can be achieved. Because the marginal damage or "social cost of carbon" can be difficult to estimate (Pizer et al. 2014), the carbon tax may not be set at the social optimum. Nevertheless, any tax rate should achieve a given level of emissions reduction at the lowest cost possible because it equalizes the marginal cost of reductions across all parties subject to the policy.

Despite assurances from economists that carbon taxes represent a cost-effective approach to reducing emissions, many policy makers and public citizens fear that they might impose a large burden on the economy. Such a burden might arise by raising prices for particular goods and by causing firms to reduce output and consumers to reduce demand in response. These economically depressing actions generate discomfort about the broader impacts of the tax on overall economic activity. Particular concern is often focused on how the tax might affect employment.

These public concerns about the negative economic impact of carbon taxes are cast against a number of economic studies suggesting that modest carbon taxes are unlikely to cause significant negative impacts and in some cases may have a positive effect on economic output (Anderson et al. 2007). The idea that a carbon tax could lead to economic growth is known as the *double dividend hypothesis*. The critical factor here is that the BC carbon tax is revenue neutral and used to reduce income taxes on BC households, as discussed above. Because income taxes introduce price distortions that reduce economic output, lowering income taxes through the introduction of a carbon tax can produce a double-dividend effect, wherein the tax not only reduces GHG pollution, but also raises total economic output (Pearce 1991; Tullock 1967). This double dividend suggests that the net economic effect of a carbon tax could be positive under some circumstances.[4] Some researchers have offered a challenge to the robustness of the double dividend on theoretical grounds (Bovenberg and Goulder 2000; Fullerton and Metcalf 1998), a challenge the BC carbon tax can put to the test given its size and use of revenues to directly reduce other taxes.[5]

British Columbia's Economic Growth under the Carbon Tax: Descriptive Statistics

An analysis whether the carbon tax has modified economic performance in British Columbia can start with simple observations of GDP per capita relative to the rest of Canada, which suggest either a slightly higher performance—Elgie and McClay (2013) comparing growth rates after the introduction of the tax in 2008—or slightly lower performance—Metcalf (2015) comparing relative growth rates of British Columbia before and after the tax was imposed. For instance, the real annual GDP growth rate from 2008–13 was 0.5% in BC and 0.4% in the rest of Canada.[6] But the more important key point, acknowledged by both studies, is that no defensible conclusions can be drawn without a statistically rigorous assessment that controls for the wide range of factors other than the carbon price that may have affected economic performance in British Columbia and the other Canadian provinces to which that price is being compared.

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[4] Of course, the full economic impact of the tax is intended to be positive once the reduced environmental damages from climate change are taken into account. The reversed negative impact referenced here speaks to the cost side of the equation, wherein the costs to the economy could be negative if the carbon tax is used to reduce distortionary taxes, as they are in British Columbia.

[5] As mentioned above, the BC government has reduced other taxes by more than the revenues taken in by the carbon tax, by amounts ranging from 2% to 35% per year (Metcalf 2015). Thus the tax has not been strictly revenue neutral, and any economic growth benefit that does accrue to tax reduction cannot entirely be attributed to the carbon tax.

[6] Data from Statistics Canada, 2015. Table 384-0038.

Evidence from Economic Modeling and Econometric Studies

In its first comprehensive review of the carbon tax (British Columbia Ministry of Finance 2013), the government conducted a numerical modeling study to estimate the effect of the tax on economic indicators. The review states that, "Economic analysis conducted for the carbon tax review indicates that BC's carbon tax has had, and will continue to have, a small negative impact on gross domestic product (GDP) in the province." However, details of the analysis were not provided in the review, and subsequent efforts to obtain the results of this analysis from the government were unsuccessful.

Beck et al. (2015) use a computable general equilibrium model of the Canadian economy to simulate the expected macroeconomic consequences of the BC carbon tax. Their simulations show a drop in household welfare of 0.08%, which is affected by the recycling of carbon tax revenues, and a decline in welfare of 0.13% if tax revenues were not used to offset tax breaks. These findings support the "weak" double dividend hypothesis that revenue recycling can mitigate economic losses from a carbon tax but not the "strong" double dividend hypothesis that the tax generates net economic growth on net.

Beck et al. (2015) and the British Columbia Ministry of Finance (2013) develop estimates of the impact of the carbon tax with model simulations of the policy *with and without* the tax. This approach contrasts with econometric studies, described below, that estimate observed economic outcomes against counterfactual statistical estimates of the outcomes without the policy. As with estimating the effect of the tax on emissions, these two approaches embody different assumptions, making a comparison of the approaches useful.

Metcalf (2015) uses econometric analysis to test whether growth rates in British Columbia differed from the rest of Canada after imposition of the carbon tax. He does so using difference-in-difference regressions of provincial GDP from 1999 to 2013, while controlling for other factors. He finds no statistically significant effect of the carbon tax on the province's economic growth. Metcalf asserts this finding is unsurprising, given the relative size of the tax burden, which accounts for only 5–6% of all tax revenue. He also suggests that the economic benefits of the tax cuts may have counter-balanced the direct negative effects of higher energy prices, which is the intention of an environmental fiscal reform such as a revenue-neutral carbon tax.

Yamazaki (2015) explores labor market effects of the BC carbon tax. He develops a partial equilibrium demand model for labor as a function of the carbon tax. With data from 2001 to 2013, he employs econometric methods to estimate a labor demand function using industry-level data on employment across provinces, controlling for industry, province, and time-fixed effects as well as the emissions intensity and trade intensity of an industry. His results indicate negative employment effects for emissions-intensive and trade-exposed (EITE) sectors in British Columbia but positive effects for non-EITE sectors and for the labor market overall. For instance, he estimates a 30% drop in employment in basic chemical manufacturing but gains in other sectors that more than make up for it. Yamazaki tests whether this effect is purely a demand effect or how much of it is due to supply shift—for instance, labor induced into the market by pro-growth tax cuts. He finds evidence that the supply effect is stronger than the demand effect, suggesting that the policy caused new labor to enter into the market. This shift also created a decline in the wage rate, which is expected if the labor supply shift dominates the demand shift. This result appears to imply that the tax created additional lower-wage jobs and thus may have nuanced distributional consequences, though these issues were not directly addressed in the paper.

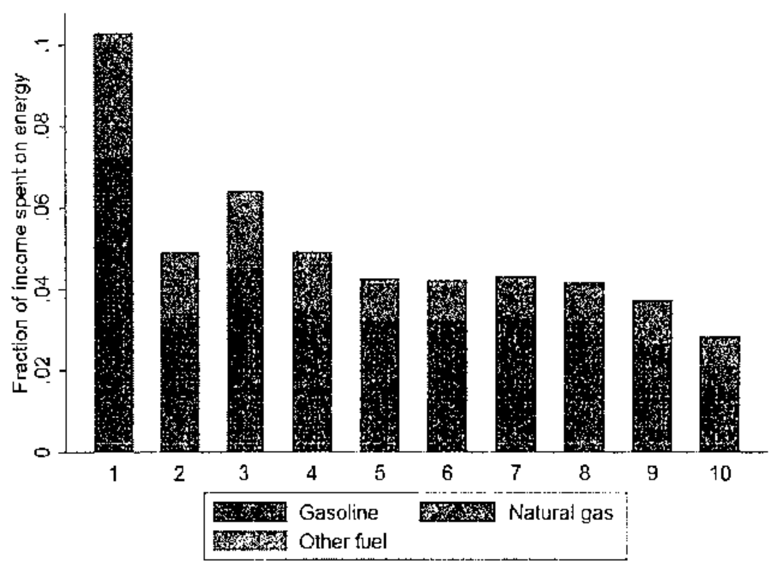
The studies just referenced examine economic effects across all economic sectors, some of which may be considered more exposed to economic hardship than others. One sector with the potential for disproportionate impact is agriculture; British Columbia has an active flow of agricultural exports and imports to and from other countries, including the United States, whose producers do not face a carbon price. BC agriculture was subject to the tax from 2008 to 2011, but as described above, the BC government opted to effectively exempt parts of the agriculture sector after 2012 under the premise of trade and competitiveness concerns (BC Ministry of Finance 2013). Rivers and Schaufele (2015) examined whether the imposition of the carbon tax between 2008 and 2011 affected BC agricultural trade flows. Using econometric estimation of trade flow (net exports and imports) equations, and controlling for heterogeneity and other key factors, they could find no statistically significant impact of the carbon price on BC agricultural trade flows.

In summary, empirical evidence on the effects of the BC carbon tax on economic performance—though based on a somewhat limited number of studies—suggests little net impact in either direction. There is some evidence of negative effects in emissions-intensive sectors, such as cement, but the positive impacts in other sectors appear to compensate for those effects.

Distributional Effects within British Columbia

A persistent concern relating to taxes on energy, carbon, and certain other types of consumption goods is that they can be regressive, weighing more heavily on low-income than on high-income households. The basis for this concern is illustrated in **Figure 3**, which uses data from the annual Survey of Household Spending conducted by Statistics Canada to estimate expenditure on energy goods as a share of income. Households in the lowest-income decile in British Columbia report spending approximately 10% of total income on carbon-based energy goods (electricity is excluded from this figure because it is nearly 100% carbon free in British Columbia, and so is not significantly impacted by the carbon tax). The large majority of expenditures for these goods are for gasoline, at approximately 7% of total income. In contrast, households in the upper half of the income distribution reported spending only about 4% of total income on energy goods. All else equal, it follows that increases in the price of energy goods resulting from a carbon tax would reduce disposable income by a larger amount for lower-income households than for higher-income households.

Figure 3. Expenditure on energy as a share of income by household income decile for BC households



Source: Data from Statistics Canada Survey of Household Spending (2009).

Implementation of the carbon tax was sensitive to this issue. The revenue recycling system that accompanied the tax's introduction allocated a substantial portion of the total revenue that was collected by the tax to low-income households, with the goal of alleviating concerns related to its distributional incidence. The revenue recycling mechanisms include the Low Income Climate Action Tax Credit, which (in 2011) returns as much as $115.50 per adult and $34.50 per child to households with incomes of less than $31,700 (for singles) or $37,000 (for couples). In addition, reductions in the personal income tax rate were implemented on the first two income tax brackets (a 5% reduction in the tax rate for households with income up to about $75,000), resulting in a larger reduction in the average tax rate for low-income individuals compared with high-income individuals.

Some analysis has been conducted to determine the ultimate incidence of the tax, accounting for the revenue-recycling mechanisms that target low-income households. The original government document that accompanied the tax's introduction presented many simulations of the tax's impact on different types of households (British Columbia 2008). The model used for these simulations was very simple in that it did not account for changes in behavior following the tax, assumed 100% pass-through of the tax, and did not account for price changes other than energy goods. It suggested that, in 2008 and 2009, the tax would result in an increase in disposable income for three prototypical low-income households with incomes of $30,000 (a single mother, a senior couple, and a senior single). Overall, said the government, "Low income families are protected… most will be better off" (British Columbia 2008, 14).

Lee and Sanger (2008) use a similar static model to examine distributional incidence, but they also included indirect expenditures on carbon by assuming a carbon content for non-energy expenditures. Like the government's analysis, their analysis uses a simple micro-simulation model and assumes no behavioral response on the part of households to the tax. It also assumes that the entire incidence of the tax is passed forward to consumers. Lee and Sanger project that the carbon tax would be "moderately progressive" in the first year of its introduction. However, they find that the schedule of carbon tax increases from 2008 to 2012 is more aggressive than the accompanying measures targeting low-income households, such that the tax is forecast to be "moderately regressive" without further increases in the low-income tax credit. Figure 1 supports this conclusion, showing the steadily declining fraction of total tax revenues that are used to support low-income households. More precisely, by 2011–2012 they find that the tax and coupled revenue recycling mechanisms would result in a 0.3% reduction in income for households in the lowest-income quintile, and a 0.2% increase in income for households in the highest-income quintile.

Beck et al. (2015) conduct an analysis of the distribution of the tax using a computable general equilibrium model, which allows them to estimate the impact of the tax on both expenditures as well as on sources of income (i.e., they do not assume complete pass-through of the tax to consumer prices but instead estimate the incidence of the tax on the basis of the model's properties). They find that even before the revenue recycling measures are considered, the BC carbon tax is "highly progressive." They suggest that this finding is a result of the tax incidence falling partly on wages (and partly on the prices of energy goods). Because low-income households derive most income from government transfers, they are insulated from falling real wages. In contrast, high-income households derive most income from wages and so bear most of the incidence of the tax. Beck et al. (2015) also report that the revenue recycling measures make the tax more progressive.

Beck, Rivers, and Yonezawa (2015) use a similar model to estimate the differential impacts of the tax on urban and rural households, a key point of contention related to introduction of the tax. They find that rural households were initially disadvantaged by the tax, but that the introduction of a northern and rural homeowner tax credit was sufficient to make these households net beneficiaries, on average, from the tax.

Public Perception of the Tax

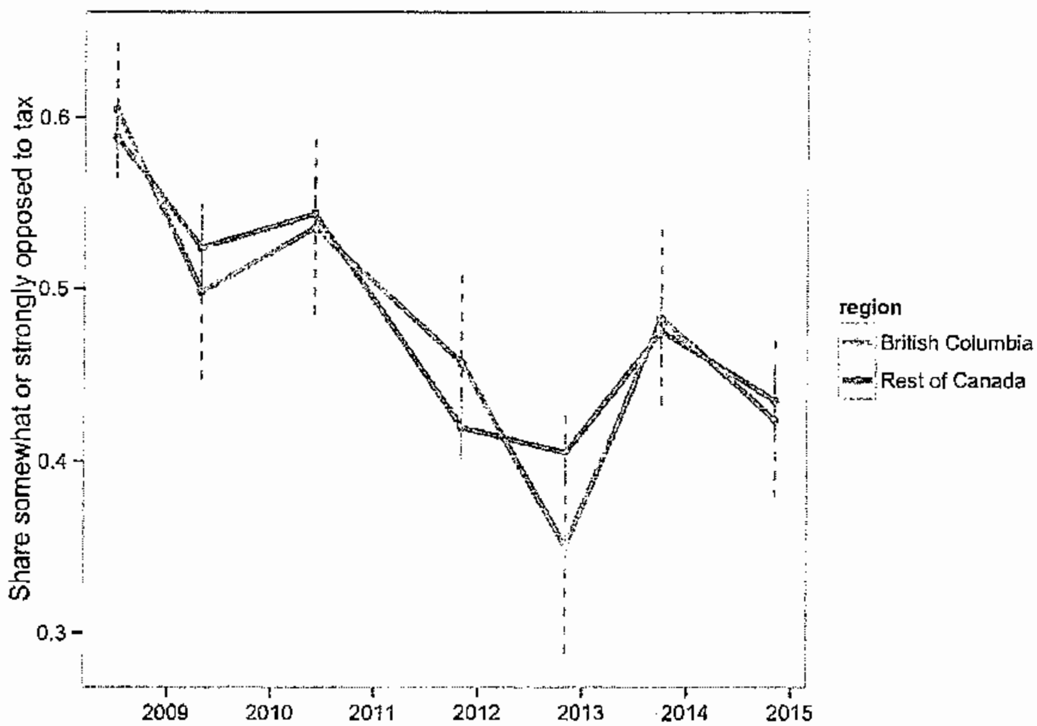
Although carbon taxes have long been supported by economists and other policy analysts advocating for cost-effective reduction of GHG emissions, their implementation has been limited by a concern that public support for such measures lags significantly behind support by economists. Implementation of the tax in British Columbia allows decision makers to understand how public support for a carbon tax unfolds after the tax has been implemented.

Residents of British Columbia have been polled regularly regarding their support for or opposition to the carbon tax. The polling firm Environics has conducted polls roughly annually since the tax was introduced. These polls use a standard survey methodology, sampling between 1,000 and 2,000 randomly selected residents by telephone in each survey wave. Respondents both in and outside the province have been asked about their perception of the tax; residents in British Columbia have been asked whether they support the tax, and those outside the province, whether they would support introduction of a similar tax in their province. Responses are categorized as strongly support, somewhat support, somewhat oppose, and strongly oppose. In the following results, the two categories of opposition are aggregated as are the two categories of support to summarize the overall level of opposition to the tax as well as to explain opposition to the tax as a function of demographic and other variables.[7]

Figure 4 shows the main results of this polling over time. Over all waves of the survey in the figure, the carbon tax was strongly or somewhat supported by 50.5% of BC respondents and strongly or somewhat supported by 51.4% of respondents in other provinces. Support for the policy generally improves over time, although unevenly. In particular, respondents appear more favorable to the tax in polls taken in the November 2011 and later waves of the survey (support for the carbon tax in November 2011 and later polls was 57.7 compared with 46.2% prior to November 2011).

[7] This analysis is based on the Environics Institute for Survey Research Microdata files, which contain anonymized data collected for Focus Canada All computations on these microdata were prepared by the authors, who bear responsibility for the interpretation presented here.

Figure 4. Polling results on the BC carbon tax, 2008–2014



Source: Polling data was provided by Environics.
Note: Dashed lines represent 95-percent confidence intervals.

Table 5 shows the results of a regression analysis that predicts opposition to the carbon tax based on selected demographic and other variables. In the first four columns, the analysis models opposition to the carbon tax as a discrete variable that takes on a value of one if the respondent indicates that he or she somewhat or strongly opposes the tax and zero if he or she somewhat or strongly supports the tax (observations with no response or an uninformative response are dropped). The first column uses a linear probability model for the entire sample. The second column restricts the sample to respondents in British Columbia, and the third and fourth columns use the entire sample, but with probit and logit functions, respectively. The fifth column uses the entire sample and a linear model but adjusts the dependent variable so that a value of 4 indicates strong opposition, 3 indicates some opposition, 2 indicates some support, and 1 indicates strong support.

Table 5. Regression results for the determinants of opposition to the BC carbon tax

	Dependent variable: opposetax(0-1)				*oppose(1-4)*
	OLS	*OLS*	*probit*	*logistic*	*OLS*
	(1)	(2)	(3)	(4)	(5)
Age: 55 or more	0.007	0.028	0.019	0.03	0.027
	-0.011	-0.03	-0.028	-0.044	-0.023
Age: less than 30	-0.113***	-0.074	-0.294***	-0.475***	-0.238***
	-0.018	-0.053	-0.046	-0.075	-0.038
Income: 30,000 to 60,000	0.035**	0.052	0.090**	0.145**	0.053*
	-0.014	-0.038	-0.035	-0.057	-0.03
Income: 60,000 to 80,000	0.039**	0.06	0.100**	0.160**	0.094***
	-0.016	-0.045	-0.042	-0.068	-0.035
Income: 80,000 to 100,000	0.014	0.02	0.035	0.057	0.025
	-0.017	-0.045	-0.043	-0.069	-0.036
Income: less than 30,000	0.044***	0.011	0.114***	0.184***	0.062*
	-0.015	-0.044	-0.04	-0.064	-0.033
Community: Small	0.064***	0.038	0.163***	0.262***	0.165***
	-0.01	-0.027	-0.025	-0.041	-0.021
Region: Rest of Canada	-0.009		-0.024	-0.039	-0.008
	-0.014		-0.037	-0.059	-0.031
Gender: Female	-0.068***	-0.077***	-0.176***	-0.282***	-0.146***
	-0.01	-0.027	-0.025	-0.04	-0.021
Year: 2009	-0.073***	-0.071	-0.187***	-0.300***	-0.173***
	-0.018	-0.047	-0.046	-0.074	-0.039
Year: 2010	-0.051***	-0.045	-0.132***	-0.212***	-0.117***
	-0.018	-0.047	-0.046	-0.074	-0.039
Year: 2011	-0.161***	-0.143***	-0.411***	-0.658***	-0.387***
	-0.018	-0.046	-0.045	-0.073	-0.038
Year: 2012	-0.181***	-0.228***	-0.465***	-0.747***	-0.404***
	-0.019	-0.052	-0.048	-0.078	-0.04
Year: 2013	-0.126***	-0.113**	-0.323***	-0.517***	-0.298***
	-0.018	-0.047	-0.046	-0.074	-0.039
Year: 2014	-0.147***	-0.167***	-0.376***	-0.603***	-0.398***
	-0.019	-0.046	-0.048	-0.077	-0.04
Constant	0.574***	0.577***	0.189***	0.304***	2.812***
	-0.021	-0.042	-0.053	-0.085	-0.044
Observations	10,339	1,357	10,339	10,339	10,339

Note: The first column is a linear probability model on all survey respondents wherein the dependent variable is a dummy that takes on a value of 1 if the respondent opposes (somewhat or strongly) the carbon tax. The second column restricts the sample to BC residents. The third and fourth columns are similar to the first but with probit and logit specifications, respectively. The fourth column uses a numerical dependent variable that takes on a value of 4 if the respondent strongly opposes the tax and 1 if the respondent strongly supports the tax (with 2 and 3 for somewhat support and oppose).

Coefficient estimates in all models are similar in sign and meaning. In particular, young people (under 30) are much less likely to oppose the tax than others. On average, being young reduces the probability that a respondent states opposition to the tax by 11 percentage points. Given that the average level of support for the policy is about 50%, this finding implies that young people are more than 20% more likely to support a carbon tax than older people. Likewise, people in high-income households (more than $100,000 per year) are significantly less likely to oppose the tax than others. In fact, opposition to the tax increases smoothly with reductions in household income and is highest for the lowest-income households. Specifically, households with an income of less than $30,000 per year have a probability of supporting the tax that is about 4.4 percentage points lower than households with incomes greater than $100,000. Households in small communities (fewer than 100,000 people) are also significantly more likely to oppose the tax. The analysis suggests that households in small communities have a 6.5% greater probability of opposing the tax than residents of large cities. Likewise, males are much more likely (by 7 percentage points) to state opposition to the tax than females. Support for the tax does not appear to be different in British Columbia than in other parts of Canada, as suggested in **Figure 4**. Finally, opposition to the tax appears to have declined substantially over time, consistent with the trends in **Figure 4**.

The model can be used to construct a profile of respondents who are most likely to support the tax and those who are more likely to oppose the tax. For example, a middle-aged male, with low or middle income, living in a small community has roughly a 70% chance of opposing the tax. On the other side, a young female with high income living in a large urban area has less than a 40% chance of opposing the tax (i.e., more than 60% probability of supporting the tax).

In addition to survey responses from telephone polls, elections provide another useful point of evidence relating to public support for the carbon tax. British Columbia has fixed election dates, and elections were held within one year of the tax's introduction (in May 2009). Polling from this period suggests that BC residents were roughly evenly divided on the carbon tax, which was certainly a key issue for voters at the time of the election. As mentioned above, the main opposition New Democratic Party ran an "Axe the tax" campaign, promising to replace the tax with a cap-and-trade system if elected (Harrison 2013). The incumbent Liberal party, which introduced the tax, won both the popular vote and seat shares, which changed little compared with share after the 2005 election. Importantly, environmental NGOs were strong supporters of the carbon tax and active during the election; they likely played a role in the election outcome, in particular by encouraging some environmentally motivated voters to support the Liberals, normally considered the business-friendly party in British Columbia. By the time of the 2013 election, the New Democratic Party had changed its position on the carbon tax, such that the tax was no longer an important election issue.

Conclusion and Policy Implications

British Columbia has given the world perhaps the closest example of an economist's textbook prescription for the use of a carbon tax to reduce GHG emissions. The tax covers a wide base, started low to ease the transition, and rose to a more substantive level, roughly in line with recent mid-range estimates of the marginal damages per ton or the "social cost of carbon" (Pizer et al. 2014) and the highest broad-based carbon price in practice today (2015). The intended use of tax revenues is to lower preexisting distortionary income taxes on businesses and households as well as to target transfers to presumptively disadvantaged low-income households. Reporting of the sources and uses of carbon tax funds is subject to a highly transparent process, under which politicians and their constituencies can track how the revenues are used each year. Given these features, the BC carbon tax provides an excellent field test of a widely prescribed policy.

This analysis has assembled and reviewed existing studies of the BC carbon tax's effect on emissions, economic performance, distributional outcomes across household-income levels, and public acceptance. It also presented an original statistical analysis of household perceptions of the tax in British Columbia or a hypothetical similar tax in other Canadian provinces. Although the published work in this area is fairly thin in quantity, findings are fairly consistent across studies within a category and are consistent with economic and demographic theory. Key messages from this assembled body of work follow.

Signals of Success

The primary objective of the BC carbon tax is to reduce GHG emissions, and essentially all studies show it is doing just that, with reductions 5–15% below the counterfactual reference level. Some studies suggest that the tax has an amplified effect on fuel-consuming (emitting) behavior above that produced by an equivalent change in fuel price. Those studies provide a range of explanations, and also find consistency with results on other taxes and policy interventions that produce outsize responses.

A secondary goal of the carbon tax is fiscal reform—to enable the use of a tax on "bads" (pollution) to displace a tax on "goods" (labor and capital), with the attendant possibility that a double dividend—pollution reductions and economic growth—might be produced. The evidence, although not decidedly pointing to a strong form of double dividend, tends to show no statistically significant effect at all on net growth for the province. At minimum, this finding suggests any negative economic effects are minimal. Studies do not estimate the economic benefits from avoided climate change, which would also contribute to policy success.

A main concern regarding implementation of a carbon tax (shared with other consumption taxes) is that the incidence of the tax may fall especially on lower-income households. This concern was addressed by dedicating a portion of revenues to low-income tax credits and to cuts in the lowest-income tax brackets. Existing analysis confirms that this measure mitigated any regressive impact of the tax when it was implemented. However, there is debate about the incidence of the tax as it was scaled up, because tax rebates for low-income households were not increased proportionately to the tax rate. The body of research does agree that the overall effects on distribution of income are likely to be small.

Although economists often prescribe carbon taxes, implementation is rare because of limited public support. Implementation of the carbon tax in British Columbia provides a case study of support for a carbon tax post-implementation. Using multiple waves of polling data, the analysis presented here finds that support for the carbon tax in British Columbia has increased, such that three years after implementation it has achieved majority support.

Shortcomings

Although the tax appears to be a success on many fronts, it has some potential shortcomings. First, although the empirical literature suggests that the tax has reduced emissions from covered fuels in British Columbia, no one knows if it has led to emissions "leakage"—that is, whether some observed emissions reductions in British Columbia are associated with emissions increases elsewhere.[8] No studies are known to have attempted to quantify the magnitude of this effect.

Second, although the carbon tax in British Columbia was originally implemented as a "textbook" policy, with wide coverage, no exemptions, and use of revenue for broad-based tax cuts and low-income tax credits, deviations from the policy have occurred in recent years. Exemptions from the tax were granted starting in 2012 to some agricultural sub-sectors and in 2014 to liquid fuel use for the entire agricultural sector. Rather than attempting to increase the (already wide) coverage of the tax, coverage has been slightly narrowed over time. In addition, broad-based tax cuts that accompanied the tax in its original

[8] For an analysis of leakage from the California cap-and-trade program, see Caron et al. (2015).

implementation have more recently been used to support particular industries (especially the film production industry) through targeted tax credits. These trends likely reduce the cost-effectiveness of the tax overall.

Finally, although the tax is now supported by more than half of the BC population, it remains a politically difficult policy to implement, because support and opposition are concentrated in particular groups. Opposition to the tax remains high in middle- and low-income, older, male, and rural groups, which are important electoral demographics.

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Nicholas Institute for Environmental Policy Solutions

The Nicholas Institute for Environmental Policy Solutions at Duke University is a nonpartisan institute founded in 2005 to help decision makers in government, the private sector, and the nonprofit community address critical environmental challenges. The Nicholas Institute responds to the demand for high-quality and timely data and acts as an "honest broker" in policy debates by convening and fostering open, ongoing dialogue between stakeholders on all sides of the issues and providing policy-relevant analysis based on academic research. The Nicholas Institute's leadership and staff leverage the broad expertise of Duke University as well as public and private partners worldwide. Since its inception, the Nicholas Institute has earned a distinguished reputation for its innovative approach to developing multilateral, nonpartisan, and economically viable solutions to pressing environmental challenges.

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referred to in the Affidavit
of [illegible] #2
sworn before me this 18th day
of December 2014

[signature]

A Commissioner for taking Affidavits
within British Columbia

CANADA'S **ECOFISCAL** COMMISSION
Practical solutions for growing prosperity

PROVINCIAL CARBON PRICING AND COMPETITIVENESS PRESSURES

Guidelines for Business and Policymakers

November 2015

Elizabeth Beale
Dale Beugin
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Don Drummond
Nancy Olewiler
Christopher Ragan

EXECUTIVE SUMMARY

Carbon pricing in individual Canadian provinces—if not matched by equivalent carbon prices in other jurisdictions—can potentially create competitiveness pressures on individual economic sectors. A sector's "carbon costs," as a share of its GDP, and its "trade exposure" are two key determinants of these pressures.

Data analysis for British Columbia, Alberta, Ontario, and Nova Scotia suggests that these pressures are significant for only a few sectors, representing only a small share of total provincial economic activity. Overall, the business community should not perceive carbon pricing as a significant economic threat.

The identification of competitiveness pressures also relies on firm-level data that is generally not publicly available. Differences in cost structures among firms within a sector, firms' abilities to influence their selling prices, the extent of firms' responses to carbon pricing, and the stringency of policies in other jurisdictions all need to be examined to determine which firms are genuinely exposed to competitiveness pressures. Policymakers will need access to firm-level data to assess the credibility of firms' claims of significant exposure.

For those firms and sectors facing genuine competitiveness pressures, governments can design the carbon pricing policy to address these challenges while still retaining the policy's overall effectiveness at reducing greenhouse gas emissions in a cost-effective manner. Any measures designed to support specific firms or sectors should be targeted, transparent, and temporary.

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PROVINCIAL CARBON PRICING AND COMPETITIVENESS PRESSURES

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Canada's Ecofiscal Commission

1. Introduction

Canada's Ecofiscal Commission has previously made the case that Canadian provinces stand to benefit from implementing broad-based carbon pricing policies.[1] By altering market incentives, carbon pricing drives reductions in greenhouse gas (GHG) emissions, contributing to global efforts to avoid costly impacts of climate change. Carbon pricing also creates incentives for innovation, helping to position Canadian firms to compete in increasingly carbon-constrained markets. Carbon pricing may also improve market access for Canadian resource products. Finally, carbon pricing achieves these outcomes more cost-effectively than alternative, regulatory policy approaches.

Broadly based carbon pricing, while essential for driving a cost-effective reduction in GHG emissions, would represent a very small share of the overall Canadian economy. For example, even if 85% of Canada's current annual GHG emissions (roughly 700 Mt) were priced at $30 per tonne, the revenue raised would be less than 1% of Canada's national income, as measured by its gross domestic product. In aggregate terms, therefore, the direct economic impact of comprehensive carbon pricing would be very small. However, since different sectors vary considerably in their emissions profiles, the impact of carbon pricing policies will also vary significantly across sectors, and even across firms.

In particular, policy actions by provinces may have a short-term impact on the ability of some Canadian businesses to successfully compete in their market environments. In the run-up to the UNFCCC Conference of the Parties in Paris in December 2015, it is increasingly clear that the path toward global climate policy is complex. Even though global emissions reductions are the ultimate policy goal, not all countries will implement carbon policies at the same pace or stringency. During this period of "uneven" policy adoption, Canadian provinces implementing carbon pricing may have more-stringent policies than other jurisdictions, and these policy differences may lead to pressures on a firm's competitiveness. This paper examines the extent to which such competitiveness pressures may arise from carbon pricing policies implemented by Canadian provinces.

Only a few regions have already implemented some form of carbon pricing—including British Columbia, Alberta, Quebec, California, and the European Union. Ontario has recently announced its intention to do so in the very near future. China has a number of cap-and-trade pilot programs, and India is in the process of implementing a carbon tax. While the United States is moving forward with national regulations for electricity generation and individual states are taking action, no national U.S. carbon price seems imminent. Thus far, with the exception of B.C.'s policy, carbon prices in Canadian provinces remain less than US$20 per tonne. Significant differences in carbon prices across jurisdictions generate the possibility that some firms in some regions will experience a competitive disadvantage.

However, the presence of competitiveness pressures need not be an obstacle to implementing effective policy for Canadian provinces. While such pressures do pose real challenges, they apply only to a few industries. The smart design of carbon pricing policy can address these challenges by including targeted, transparent, and temporary measures of support.

1 See *The Way Forward: A Practical Approach to Reducing Canada's Greenhouse Gas Emissions*, Canada's Ecofiscal Commission, April 2015.

This paper uses Canadian provincial data to explore the extent of the pressures on competitiveness caused by carbon pricing policies. Our approach has two main benefits. First, it assesses the scale of these pressures, using a transparent, evidence-based framework. We find that the pressures on competitiveness are quite small when expressed as a share of the country's total economic activity. Second, policymakers and emitters can use our framework to discuss cost-effective policy measures to address competitiveness.

2. What do we mean by "competitiveness pressures"?

Competitiveness is a concept that has different meanings, depending on the context and the audience. In considering competitiveness pressures created by carbon pricing policy, we must be explicit about what we mean by the term—as well as what we exclude from the relatively narrow definition used here.

Most generally, any individual firm's competitiveness reflects its ability to succeed in its business environment. Within any province, its firms' competitiveness depends on multiple factors. Corporate income-tax rates, foreign-exchange rates, the prices of locally supplied inputs, regulations of various kinds, wage rates, the proximity to key markets, the quality of supply chains, the creativity of management, and the ability to recruit and retain qualified workers are only a few of the many factors that determine whether firms in a given jurisdiction can successfully compete with firms elsewhere. Carbon pricing is only one factor in a larger and more complex story.

In the context of carbon pricing policy, competitiveness pressures can arise when there is a higher carbon price in one Canadian province than in other jurisdictions—either foreign or domestic. In these cases, provincial firms competing in national or international markets might experience a "carbon disadvantage" relative to firms outside the province. Given that Canadian firms have traditionally focused much of their trade within the North American market, it is the policy differences between the various Canadian provinces and between Canada and the United States that are particularly important for this discussion.

In short, carbon competitiveness pressures come from carbon-price *differentials* between trading partners, not the absolute level of the carbon price. Under a uniform global carbon price, for example, there would be no competitive disadvantage between Canadian and foreign firms.[2] On the other hand, using carbon pricing in any one province—while other jurisdictions have either no or lower carbon prices—can create challenges for firms and industries competing in international or interprovincial markets.

Differences between carbon prices at home and abroad can have both economic and environmental implications. When we talk about competitiveness pressures in this report, we refer only to competitive impacts on industries between jurisdictions with carbon prices of different stringency. Provinces with higher carbon prices might see some current or future production and investment move toward jurisdictions with weaker policies. The result is lost economic activity in the home jurisdiction. *Leakage* is the environmental side of the same coin: if economic activity simply relocates to other jurisdictions and produces carbon emissions identical to what

Is there also a "carbon advantage"?

This paper focuses on competitiveness pressures created by carbon pricing, but it is also important to recognize the opportunities for creating "carbon advantages" for Canadian firms.

As other jurisdictions implement their own ecofiscal policies, the global market for low-carbon innovations naturally grows. Implementing carbon pricing policies will make some domestic firms better positioned to compete in this emerging low-carbon global economy (NRTEE, 2012).

Advantages arise in several different ways. The most direct are from carbon-reducing sectors. Research by McKinsey & Company (2012), for example, suggests that Canadian firms could have increasingly valuable competitive advantages in sustainable resource development, carbon capture and storage, uranium mining and processing, and hydroelectricity expertise.

Competitive advantages could also come from those firms and industries better positioned to compete under carbon constraints as a result of their lower emissions intensity. One modelling analysis for Ontario, for example, finds that its electricity, pulp and paper, and food manufacturing sectors could have a carbon advantage relative to North American competitors in a carbon-constrained market (Sawyer, 2013).

2 A uniform global carbon price would drive a global adjustment away from carbon-intensive activities and would involve important transitional costs. But these costs of structural adjustment to a low-carbon world are distinct from the competitiveness pressures we emphasize here.

existed in the home jurisdiction, Canadian provinces risk bearing the economic costs of lost production or investment with no net change in global GHG emissions.

The impacts on business competitiveness will change over time. Well-designed carbon pricing policies start with low prices that then increase steadily. In the short term, differences between carbon prices in Canadian provinces and other jurisdictions will tend to be small, and pressures on competitiveness will therefore also be small. In the very long term, since it is likely that jurisdictions will converge on similar carbon prices, these pressures will also tend to diminish. The important pressures on competitiveness are thus most likely to appear in the medium term, but only if policy in Canadian provinces gets far ahead of policy in other jurisdictions.

Finally, it is worth noting that most economic research has been unable to document a significant impact of carbon pricing on investment and production. Most studies of carbon competitiveness—for both proposed and historical policies in jurisdictions such as the European Union, the United States, and Canada—tend to find only small implications for the economy (e.g., Quirion & Hourcade, 2004; Aldy & Pizer, 2007; Reinaud, 2008, 2009; Barker et al., 2009; Morgenstern et al., 2007; National Round Table on the Environment and the Economy [NRTEE], 2009). Recent empirical research for the United Kingdom, for example, finds no evidence that the competitiveness of firms has been negatively affected by that country's climate-change policies (Bassi & Zenghelis, 2014). Given the complexity of a firm's competitiveness, and how many factors come together to influence it, perhaps it is not surprising that empirical studies find no significant relationship between it and carbon pricing.

In sum, we define "competitiveness pressures" from carbon pricing more narrowly than the broader concept of business competitiveness commonly used in economic discussions. Yet using this narrow definition is critical to isolate factors that really matter for the good design of carbon pricing policies. Many competitiveness issues are entirely independent of carbon pricing and should not be conflated. And some outcomes from carbon pricing—such as structural changes within industry—are not really about carbon competitiveness at all, but instead are part of a cost-effective global transition toward an economy with lower overall GHG emissions. The complexity of these issues underlines the importance of using data and evidence-based analysis to assess the sector-by-sector competitiveness pressures from carbon pricing.

3. Which sectors are most exposed to competitiveness pressures?

Only a small subset of the Canadian economy is likely to experience competitiveness pressures from carbon pricing. Given that firm-level data is not publicly available, we use data at the sector level to consider how these pressures vary across the different sectors within selected provincial economies. We begin by using two key criteria to identify potentially vulnerable sectors: carbon cost and trade exposure.

Carbon cost measures the dollar value of a sector's carbon-price payments as a share of that sector's gross domestic product (GDP)—assuming a carbon price of $30 per tonne of CO_2e, the value of British Columbia's current carbon tax. This value is also equal to the carbon price multiplied by the sector's *emissions intensity*.[3] Sectors with higher carbon costs might use more energy, or rely on processes that produce substantial GHG emissions. The emissions intensity estimated for each sector includes both the *direct* GHG emissions produced by the sector as well as the *indirect* emissions embedded in the electricity used by the sector. The pressure on competitiveness therefore reflects the carbon costs from both direct and indirect emissions.

A sector's *trade exposure* measures the extent to which firms in that sector compete with firms from outside their province.[4] Trade exposure matters because it is one key factor in determining whether emitters can pass their carbon costs on to their consumers in the form of higher prices. If firms sell undifferentiated products and are price-takers—as is the case in many international commodities markets—they cannot pass province-specific carbon costs on to their customers. In this case, the decline in firms' profits reflects the decline in their competitiveness. On the other hand, if firms sell highly differentiated products and have some influence on their products' selling price, some fraction of carbon costs can be passed on to both domestic and foreign customers, thus dampening the impact of the carbon price on their bottom line.

3 Carbon cost is measured here as a share of each sector's GDP, assuming that firms' production methods are unchanged. Since most firms will adjust their production methods to a carbon price, especially over time, this measure will be an overstatement of the sector's true carbon cost. (In the economic model, real GDP for each sector is expressed in 2002 dollars; a carbon price of $30 in 2015 is thus converted into approximately $23 for the same base year.) Alternatively, a sector's carbon costs could be expressed as a share of the value of total sectoral revenues. Since revenues are necessarily larger than value added (GDP), this approach would result in lower estimates of carbon costs for all sectors.

4 Trade exposure for a sector is defined as the sum of the sector's imports and exports divided by the sum of the sector's production and imports (California Air Resources Board, 2012). A sector with a trade exposure of zero thus has neither imports nor exports. A sector with a trade exposure of 100% exports all the goods it produces (exports = production).

We examine these two characteristics for various sectors within selected Canadian provinces. For reasons of confidentiality, provincial-level data with the required sectoral detail is not available to the public. Instead, we use "model data," which in this case means the data underpinning a regionally disaggregated computable general equilibrium (CGE) model. The model contains rich sector-level detail on employment, production, and GHG emissions. With model data, the sectoral details are a function of the model's representation of provincial economies. While the model is closely calibrated to provincial data, it remains an approximation of provincial economic structure.[5]

Which specific sectors are most emissions intensive and trade-exposed in each province? Not surprisingly, it varies across the provinces. To highlight these differences, we examine four provinces to show the range of exposure to carbon pricing, but also to identify specific sectors most likely to be vulnerable. British Columbia shows the profile for an economy with a low-carbon, hydroelectric energy system. Alberta represents a resource-intensive economy, Ontario a manufacturing-intensive economy, and Nova Scotia a small economy with only a few specific emitters.

Below, we consider key details for each of the four provinces. These points highlight differences and similarities between provinces, but also draw out insights about vulnerable sectors in each case. Overall, a common theme emerges across all four provinces: the vast majority of economic activity—including services and other manufacturing—is not exposed to significant competitiveness pressures.

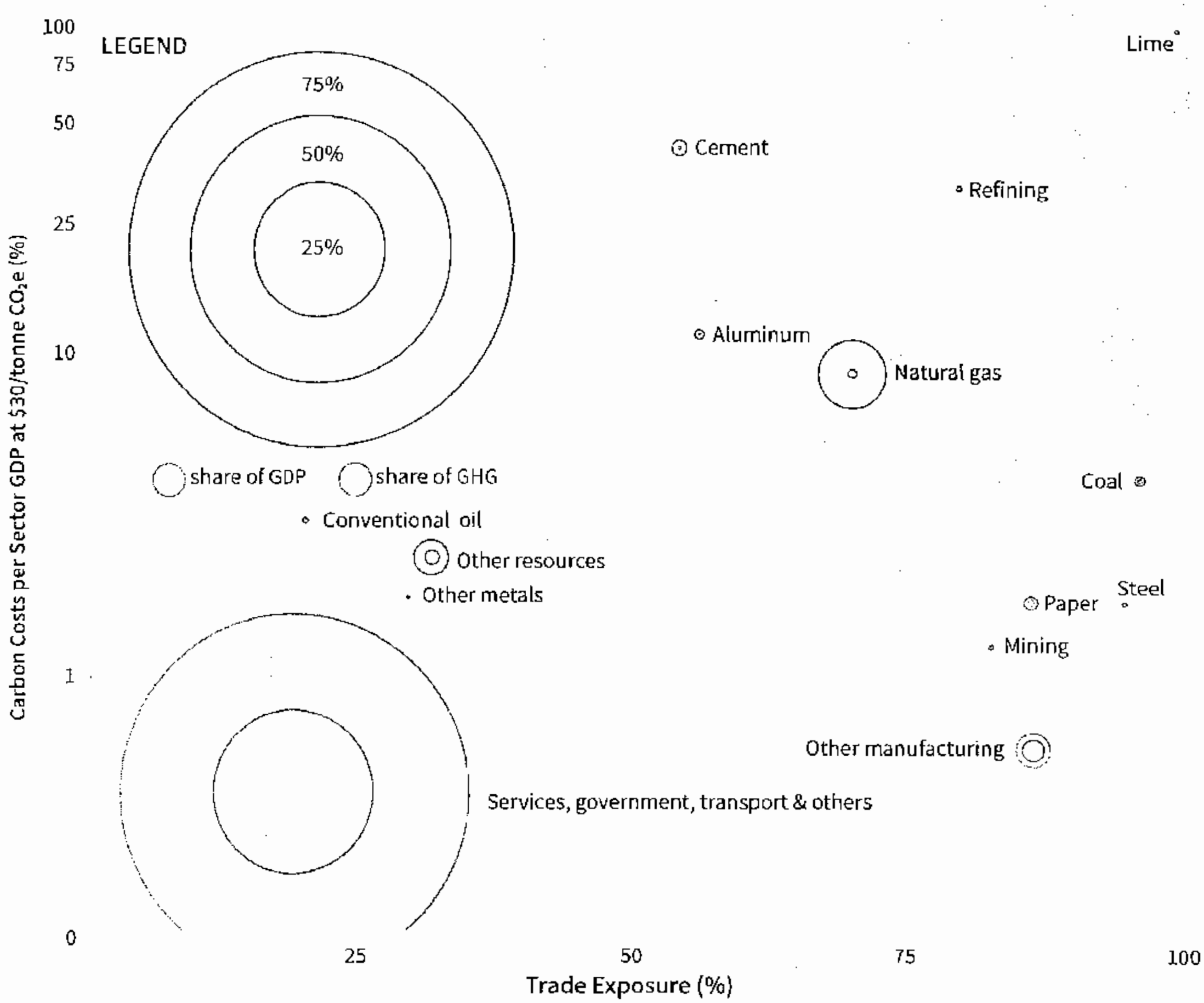
Figures 1a, 1b, 1c and 1d show how specific sectors in these four provinces are more or less exposed to pressures created by carbon pricing. Each sector is plotted showing its carbon costs on the vertical axis and its trade exposure on the horizontal axis. The farther a sector is positioned toward the upper right-hand corner of the figure, the more vulnerable it is to these two competitiveness pressures. The size of the bubble representing each sector shows its contribution to provincial GHG emissions (red) and GDP (blue). A larger bubble indicates a larger sector.[6]

5 Working with Navius Research, we developed provincial input-output tables (representing the flows of goods and services between different sectors and provinces) for 2015 based on a CGE simulation of current policy. The model is calibrated to historical provincial data.

6 Electricity generation does not appear in this analysis as a distinct sector, because the GHG emissions from electricity generation are allocated to the purchasers of the electricity in other sectors. These are each sector's indirect emissions, as discussed earlier.

British Columbia

Figure 1a: Competitiveness Pressures by Sector in British Columbia



The centre of each sector's bubble reflects that sector's trade exposure (horizontal axis) and its carbon costs (vertical axis; log scale). The size of each bubble reflects the sector's share of provincial GDP (blue) and share of provincial GHG emissions (red).

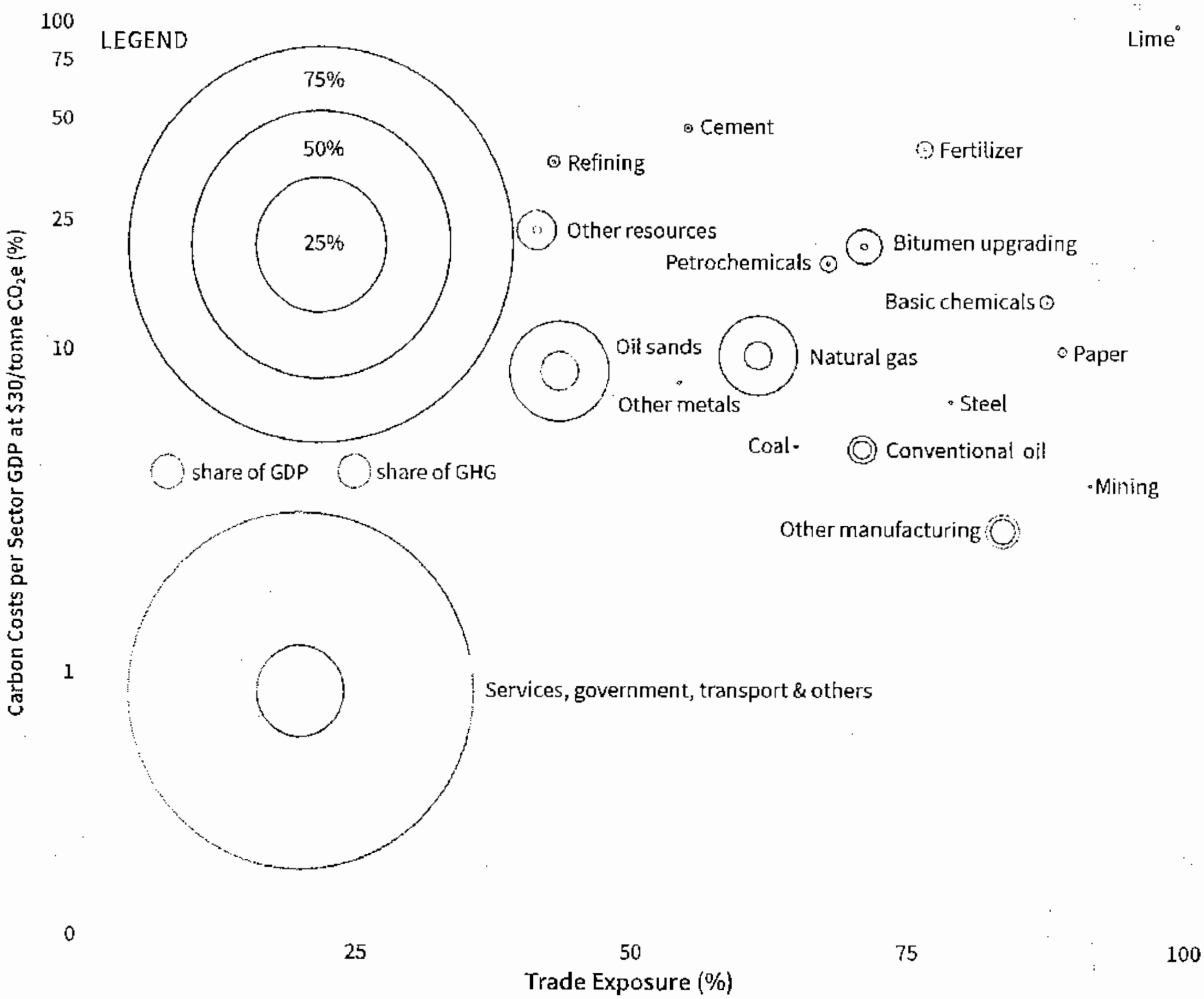
Source: Modelling analysis from Canada's Ecofiscal Commission and Navius Research.

- The cement sector appears to be one of the most exposed to competitiveness pressures, with particularly emissions-intensive production. Note that much of the GHG emissions produced in cement manufacturing come from "process emissions"—those produced during the chemical processes involved in cement production—rather than from the combustion of fossil fuels. Such process emissions are not currently covered by the province's carbon tax.
- Refining is the other particularly emissions-intensive sector in B.C., though it is quite small, contributing less than 0.1% of provincial GDP and less than 1% of provincial GHG emissions.
- The natural gas sector is also exposed to competitiveness pressures, and makes up about 2% of provincial GDP. Yet the sector is only one-fifth as emissions intensive as the cement sector on average.[7] Though not shown in the figure, emissions intensity varies substantially across different natural gas projects, from conventional fields to shale and tight gas plays.
- Finally, liquid natural gas (LNG) facilities are not included in the analysis, as no projects are currently completed. Should the sector grow, however, it would likely be quite exposed to competitiveness pressures. Interactions with B.C.'s evolving tax treatment of LNG facilities would also play an important role in determining the sector's overall competitiveness.

7 The vertical scale in Figure 1 is in log form, so the vertical distance between carbon costs gets compressed as the carbon cost increases. The vertical distance on the graph between 1% and 10% is the same as the distance between 10% and 100%.

Alberta

Figure 1b: Competitiveness Pressures by Sector in Alberta



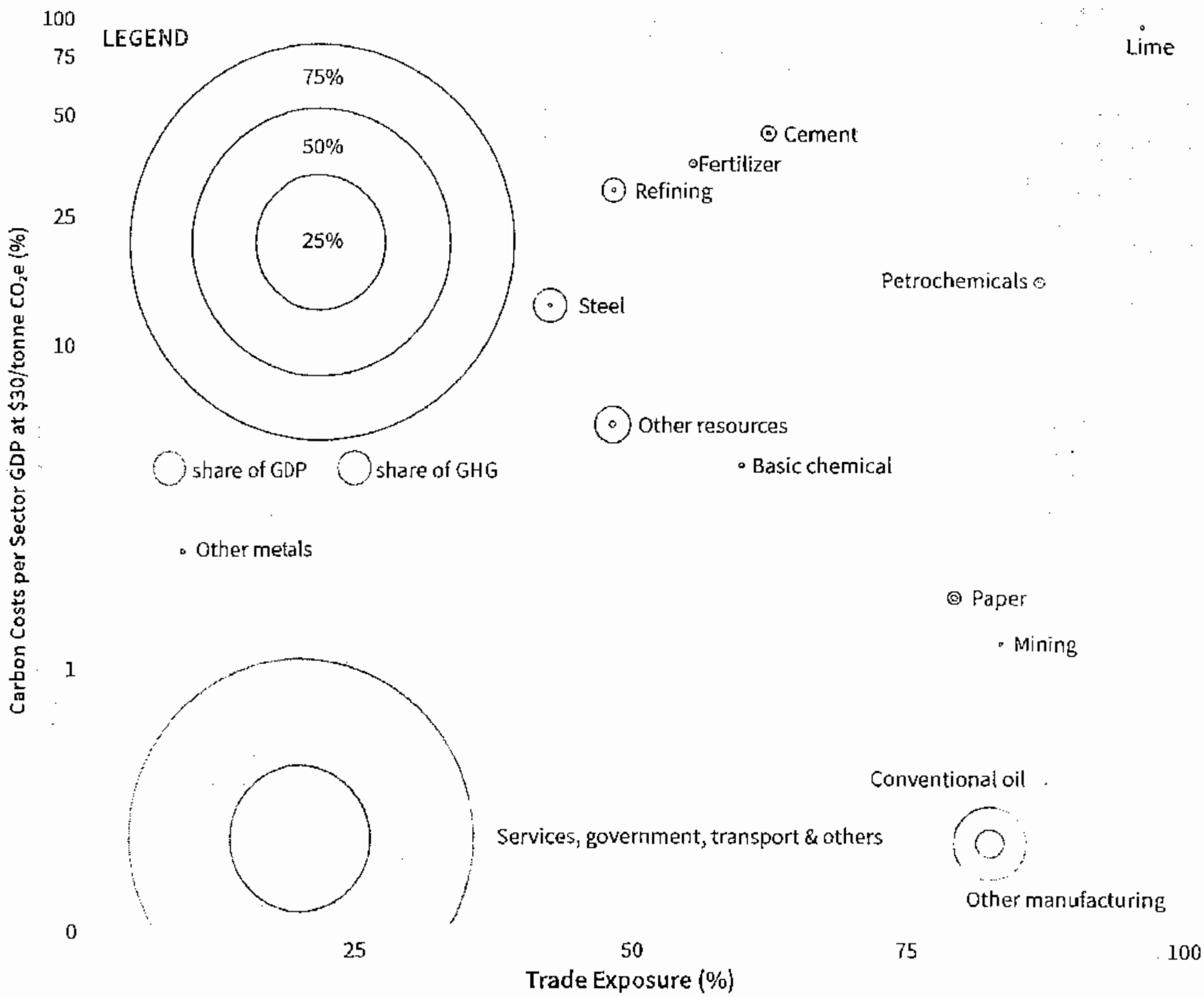
The centre of each sector's bubble reflects that sector's trade exposure (horizontal axis) and its carbon costs (vertical axis; log scale). The size of each bubble reflects the sector's share of provincial GDP (blue) and share of provincial GHG emissions (red).

Source: Modelling analysis from Canada's Ecofiscal Commission and Navius Research.

- A much larger share of Alberta's economy is exposed to competitiveness pressures, given the importance of resource extraction sectors. The oil and natural gas sectors collectively make up around 20% of provincial GDP. Still, interactions with other fiscal policies are a critical factor not considered here. In particular, royalties paid by oil sands companies are currently based on the difference between revenues and the sum of current and capital expenditures. As a result, these royalty payments would decrease as carbon prices rise, thereby offsetting some of the impact on competitiveness (Bošković & Leach, 2014).
- Indirect GHG emissions matter much more for provinces that rely on coal-fired electricity generation, such as Alberta and Saskatchewan. With a much more emissions-intensive electricity supply, a broad-based carbon price would lead to higher electricity costs. On the other hand, switching to gas-powered generation likely represents relatively low cost abatement; over time, indirect emissions are likely to decline in response to effective carbon pricing policies.
- Even though the oil and gas sectors are exposed to competitiveness pressures, they are not the most vulnerable sectors in Alberta. Fertilizer, chemical manufacturing, and petrochemical manufacturing are all considerably more emissions intensive and trade exposed—although they are much smaller as a share of the economy and thus may present less of a challenge for policy design.

Ontario

Figure 1c: Competitiveness Pressures by Sector in Ontario



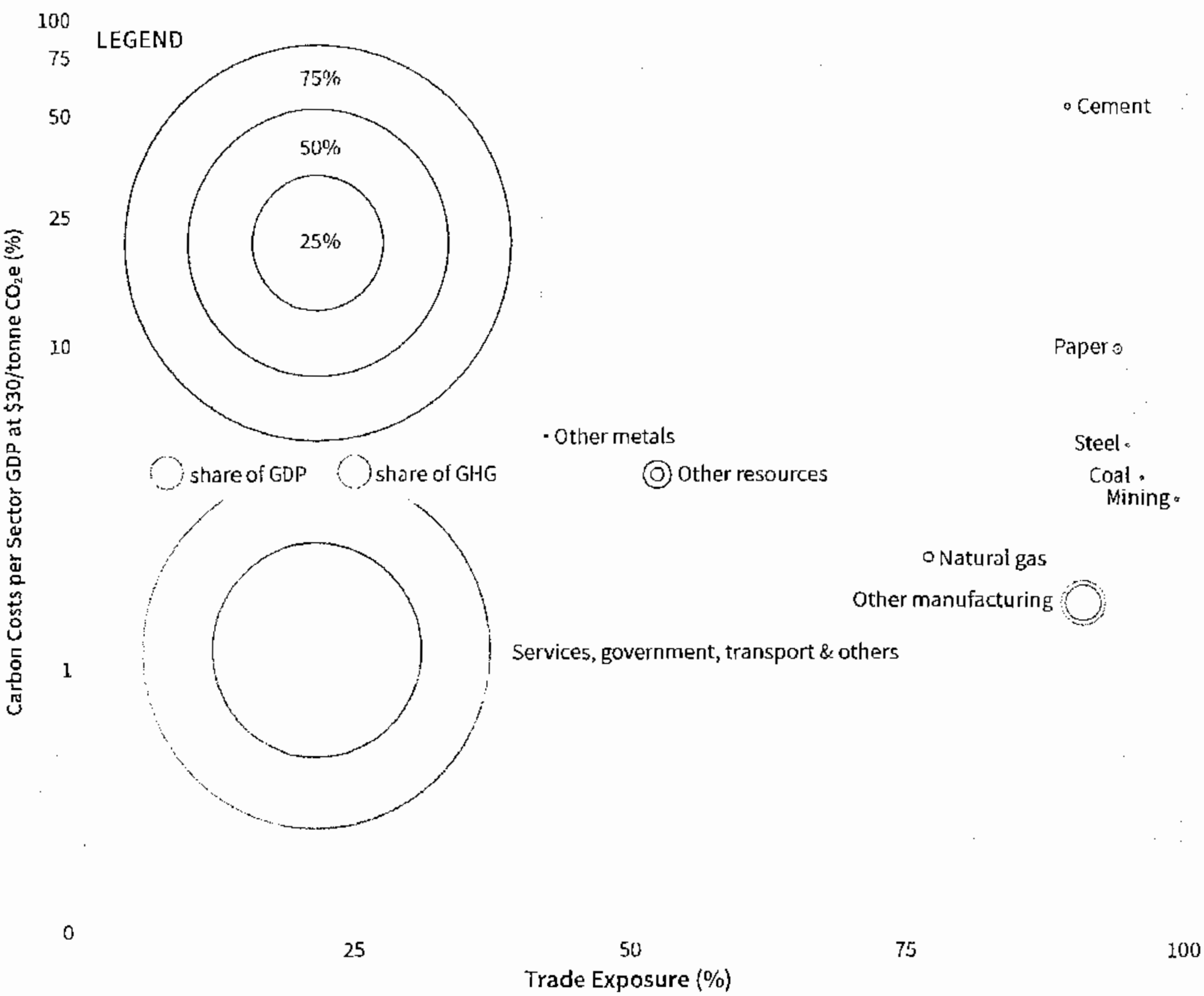
The centre of each sector's bubble reflects that sector's trade exposure (horizontal axis) and its carbon costs (vertical axis; log scale). The size of each bubble reflects the sector's share of provincial GDP (blue) and share of provincial GHG emissions (red).

Source: Modelling analysis from Canada's Ecofiscal Commission and Navius Research.

- Ontario's manufacturing sector is mostly unexposed to competitiveness pressures from carbon pricing. Other manufacturing, including industries such as vehicle and aerospace manufacturing, is highly traded, but is generally not emissions intensive. Other manufacturing makes up around 15% of Ontario's GDP.
- Only a few specific manufacturing sectors—steel, chemicals, petrochemicals, fertilizer, and refining—display a notable exposure to competitiveness pressures. Though collectively these sectors make up less than 1% of provincial GDP, they are responsible for one-quarter of Ontario's industrial GHG emissions.
- Interestingly, some of Ontario's manufacturing sectors may be better positioned to compete relative to those in other provinces. Ontario's pulp and paper sector, for example, is less emissions intensive than the pulp and paper sectors in Alberta and Nova Scotia, largely because its electricity supply is less carbon intensive, and thus its indirect emissions are smaller. If carbon pricing policies were evenly implemented across all provinces, Ontario firms could face lower carbon costs and thus have an advantage relative to those in Alberta.

Nova Scotia

Figure 1d: Competitiveness Pressures by Sector in Nova Scotia



The centre of each sector's bubble reflects that sector's trade exposure (horizontal axis) and its carbon costs (vertical axis; log scale). The size of each bubble reflects the sector's share of provincial GDP (blue) and share of provincial GHG emissions (red).

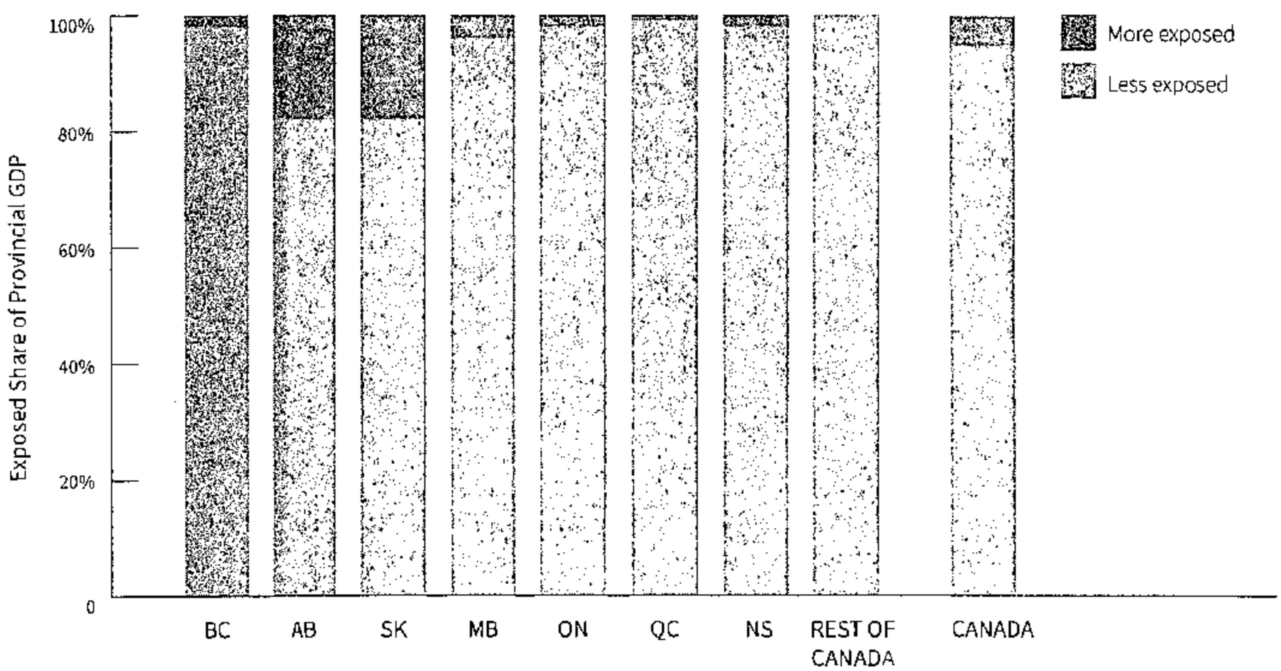
Source: Modelling analysis from Canada's Ecofiscal Commission and Navius Research.

- Nova Scotia's small size has interesting implications for its exposure to competitiveness pressures. A large share of the goods it produces—coal, gold, cement, natural gas, pulp and paper, and other resources—are exported in competitive markets, leading to a very high measure of trade exposure.
- At the same time, vulnerable "sectors" are often single facilities. For example, Nova Scotia has a single cement facility and two pulp and paper plants. These are the individual emitters in the province likely to be most exposed to competitiveness pressures.
- About 10% of the provincial economy is based on other manufacturing that has low emissions intensity and carbon costs, although considerable trade exposure.
- Future developments in the province—such as additional natural gas projects and LNG plants—would likely also be both emissions intensive and trade exposed.

4. What is the overall scale of competitiveness pressures?

Figure 1 illustrates how different sectors are exposed to competitiveness pressures from carbon pricing. As discussed, the farther a sector is to the top right of the figure (i.e., is more emissions intensive and more trade exposed), the more vulnerable it is. But to quantify a share of the economy exposed to significant pressures, we need to define a specific threshold. We categorize sectors as "more exposed" if they have both a carbon cost greater than 5% of GDP (measured at a $30 carbon price) and a trade exposure greater than 15%.[8] Figure 2 shows the share of provincial GDP coming from sectors deemed to be more exposed.

Figure 2: The Scale of Competitiveness Pressures for Canadian Provinces, 2015



The red bars show the share of GDP in each province coming from sectors with a carbon cost greater than 5% of GDP and a trade exposure greater than 15%.

Source: Canada's Ecofiscal Commission and Navius Research.

Four main observations emerge from Figure 2. First, the overall economic implications of competitiveness pressures are quite small. For Canada as a whole, only 5% of the economy is "more exposed." With the exception of Saskatchewan and Alberta (to which we return below), considerably less than 5% of each province's economic activity is exposed to competitiveness pressures. The main reason for the large-scale absence of carbon exposure is that services and non-traded goods, both of which have very low *carbon intensities*, represent a huge share of modern, developed economies. Canadian provinces are no exception. Consider, for example, the case of British Columbia. As indicated in Figure 2, that province's carbon tax, which applies directly to the use of most fossil fuels, does not have a key impact on overall business competitiveness. For non-traded goods and services, much of the carbon cost can be passed on to final consumers (households and drivers), thus significantly dampening the competitiveness pressures on that province's businesses.

8 These thresholds parallel the American Clean Energy and Security Act (H.R. 2454) proposed in the United States in 2009 (Western Climate Initiative, 2009). H.R. 2454 defines emissions intensity as emissions per dollar of sectoral production (revenues), rather than per dollar of value added (GDP). Using the 5% threshold in the context of carbon costs as a share of GDP is a more conservative approach since it leads to more sectors being classified as more exposed.

Second, while the shares of provincial GDP exposed to competitiveness pressures are generally small, the exposed sectors represent a disproportionate share of total provincial GHG emissions, as shown in Table 1. This finding is intuitive: since vulnerable sectors are *by definition* emissions intensive, their share of provincial GHGs must be larger than their share of provincial GDP. This difference has important implications and a potential tradeoff for policymakers. The general concern is that if carbon-intensive and trade-exposed firms relocate to regions with lower carbon prices, aggregate GHG emissions will not decline. This is the leakage problem discussed previously. Emissions in the carbon pricing province may decline, only to be replaced by increases in those jurisdictions with weaker carbon policies. The global effectiveness of carbon pricing policy is undermined if vulnerable sectors simply relocate their activities to other jurisdictions but leave their GHG emissions unchanged.

If policymakers choose to exempt selected sectors from the carbon policy to avoid this competitiveness/leakage problem, they will create a second important problem. Given a desire to achieve a specific emissions-reduction target, the exemption of emissions-intensive sectors from carbon pricing would reduce the effectiveness of the policy in reducing emissions and would also impose a greater burden on the remaining sectors. As is generally the case in issues of public finance, the smaller the tax base, the higher the tax rate needs to be to generate a targeted outcome. Policy can, however, be designed to address this tradeoff while maintaining incentives to improve emissions performance. We return to policy approaches below.

Table 1: Share of Provincial GDP and GHGs Exposed to Competitiveness Pressures From Carbon Pricing

	Percentage of GDP from sectors:		Percentage of GHGs from sectors:	
	less exposed	more exposed	less exposed	more exposed
British Columbia	98	2	78	22
Alberta	82	18	48	52
Saskatchewan	82	18	21	79
Manitoba	96	4	57	43
Ontario	98	2	74	26
Quebec	99	1	83	17
Nova Scotia	98	2	64	36
Rest of Canada	100	0	91	9
Canada (overall)	95	5	60	40

Third, the magnitude of the competitiveness pressures varies widely across provinces. Part of this story is differences in electricity mixes: provinces with low-carbon electricity generation—including hydro provinces such as British Columbia, Manitoba and Quebec, but also Ontario (which phased out coal-powered electricity)—have much lower indirect emissions. Part of the story is structural: emissions-intensive industries make up a larger share of some provincial economies. Alberta and Saskatchewan, in particular, with strong oil and gas sectors, emissions-intensive electricity generation, and significant chemical manufacturing sectors, will have greater vulnerability. And part of the story is policy: some provinces have already implemented policies to reduce emissions intensity, including B.C.'s carbon tax, Alberta's Specified Gas Emitters Regulation, and Ontario's coal phase-out.

Fourth, the scale of the overall competitiveness pressures is relatively insensitive to changes in the price of carbon, as seen in Table 2. We have used a price of $30 per tonne of CO_2e to define carbon costs, but the share of the economy "more exposed" increases only modestly as this price increases considerably. At $60 per tonne, 7% of the economy is more exposed; at $90 per tonne, 8% is more exposed; at $120 per tonne, the number is around 10%. Individual emissions-intensive sectors, of course, face higher carbon costs and competitiveness pressures at higher carbon prices. But the number of sectors that are more exposed does not change significantly.

This finding reinforces the idea that competitiveness pressures are much more important for some specific industries than for the economy overall.[9]

Finally, note that the thresholds used to construct Figure 2 are somewhat arbitrary. Indeed, different carbon pricing policies and policy proposals have used different benchmarks for determining vulnerability (for a summary, see Western Climate Initiative, 2009). California, for example, categorizes sectors as facing low, medium, or high competitiveness "risks" based on specific thresholds for emissions intensity and trade exposure (California Air Resources Board, 2012). California's criteria appear to be less strict than the ones used here, and allow for a very large number of sectors to be considered "at risk," even those with very limited trade exposure. California uses these categories to determine which sectors are allocated free permits under its cap-and-trade system and, as a result, has provided a large number of free permits.

Table 2: Shares of Provincial GDP More Exposed Under Different Carbon Prices

	\$30 per tonne CO_2e (% of GDP more exposed)	\$60 per tonne CO_2e (% of GDP more exposed)	\$90 per tonne CO_2e (% of GDP more exposed)	\$120 per tonne CO_2e (% of GDP more exposed)
British Columbia	2	3	7	9
Alberta	18	28	28	28
Saskatchewan	18	20	20	20
Manitoba	4	5	5	5
Ontario	2	2	2	5
Quebec	1	3	3	5
Nova Scotia	2	5	7	17
Rest of Canada	0	6	10	10
Canada (overall)	4	7	8	10

5. What's missing from this analysis?

We have now examined two of the many factors affecting the competitiveness of firms in the context of carbon pricing. And though our analysis is useful at identifying potential pressures from the policy, it also has some clear limitations, mostly arising from a lack of adequate data. There are five reasons why our analysis should not be considered a definitive assessment of the competitiveness pressures created by carbon pricing. The examination of (confidential) firm-level data is required for a more thorough analysis of these pressures.

1. Firms Respond to Carbon Prices. Our analysis cannot address how firms respond to carbon pricing. Rather, it looks only at the carbon costs as if firms made no adjustment in their production methods. In response to any significant carbon price, however, a profit-maximizing firm can be expected to reduce its GHG emissions and change its use of emissions-intensive inputs. Of course, this is exactly the point of carbon pricing: it induces substitution and innovation. Especially over time, these responses can be very significant. That these responses are not built into Figure 1 suggests that the carbon costs shown therein, as well as the percentages of GDP "more exposed" in Figure 2, should be viewed as upper bounds of the actual competitiveness pressures.

2. Firms Differ Within Sectors. Owing to data limitations, we have examined only sectoral averages for carbon costs and trade

9 The estimated shares of provincial GDP "more exposed" are also relatively insensitive to changes in the trade exposure threshold (15% in Figure 2). Almost all the sectors are identified as trade exposed, given that our measure is based on out-of-province trade. Considering only *international trade*, on the other hand, would reduce the number of sectors classified as trade exposed.

exposures. Yet different firms within any one sector vary significantly in both dimensions. Smaller firms, for example, tend to be less involved in exporting to foreign markets than are larger and more established firms, although smaller firms may be more vulnerable to loss of market share to imported products. In industries characterized by ongoing technological change, it is normal to see older production facilities operating alongside newer ones. And though both vintages of firms may satisfy the requirements of profitability, the older facilities typically use older and more emissions-intensive technologies than do the newer ones, which embody the latest and cleanest technologies. These important differences among firms within any sector underline the importance of examining firm-level data to determine the genuine competitiveness pressures associated with carbon pricing. Sector-level data can be a very useful starting point, but it is not sufficient for those designing policy.

3. Carbon Policy Elsewhere Matters. Our measure of trade exposure has an important limitation. We estimate trade exposure based on *all* out-of-province trade, and do not differentiate based on specific trading partners. As a result, the metric could overstate risks if firms in specific sectors primarily compete with firms in jurisdictions that have already implemented carbon pricing policies. Given that several provinces and U.S. states have implemented carbon pricing policy, or are in the process of doing so, competitiveness pressures could be lower than suggested in the previous section. Similarly, with the United States moving forward with electricity regulations through the Environmental Protection Agency, indirect emissions from electricity will begin to see increasing carbon costs that will be passed on to manufacturers throughout the United States, thus reducing the competitiveness pressures faced by Canadian firms. This points again to the need for more detailed data. Policymakers need to know which foreign markets Canadian firms are exporting to, and also receiving imports from, and the extent of carbon pricing policies in all those jurisdictions. Genuine competitiveness pressures on Canadian businesses cannot be ascertained without such data.

4. Market Details Matter. Another limitation of our analysis is that we do not examine the nature of each sector's product and market structure. Yet both factors affect the extent to which firms are able to pass carbon costs on to their consumers in the form of higher prices. If firms sell differentiated products, as is often the case in manufacturing industries, they generally have some ability to set their own prices. In such settings, firms will be able to pass some part of their carbon costs on to consumers. The more firms can pass on these costs, the less they are exposed to carbon competitiveness pressures.

5. Other Policies Affect Competitiveness. Finally, the broader policy context is critical. Carbon pricing policy is far from the only policy that affects business competitiveness. Other fiscal policies—such as corporate taxes and resource royalty regimes—play a major role. These various policies could also interact, depending on policy details. For example, if carbon costs are tax deductible for firms, the total amount paid in corporate income taxes could decrease under carbon pricing policy. It is also worth noting that revenues raised from a carbon pricing policy could be recycled back to the economy in a way that enhances business competitiveness. An example is in British Columbia, where part of the revenues raised by the carbon tax finance the reduction in the corporate income-tax rate, which is now the lowest in Canada. The combination of higher carbon taxes and reduced corporate income taxes could well lead to an improvement in the competitiveness of some businesses, and this is one option that policymakers in all Canadian provinces have at their disposal. Another option is to use carbon pricing revenues in more targeted ways to support vulnerable industries, as we discuss below.

In short, when attempting to identify the genuine competitiveness pressures on Canadian businesses created by the introduction of carbon pricing, it is not sufficient to rely only on an examination of each sector's emissions intensity and trade exposure. These two metrics have clear limitations and must be used carefully, and several other factors must also be examined. Figure 1 may be a useful starting point for policymakers, but by itself, it is not an adequate basis for the design of good policy.

6. What are the implications for policy?

Based on the analysis presented here, six principal lessons emerge for Canadian provinces considering how best to implement carbon pricing policies while also recognizing the importance of potential pressures on business competitiveness.

1. Competitiveness pressures from carbon pricing should not be overstated.

Competitiveness pressures do pose real economic and environmental challenges—but only for a small number of industries and a very small share of total economic activity. Most provincial economies are not both emissions intensive and trade exposed, and so are not highly vulnerable to competitiveness pressures. Moreover, as more Canadian provinces and U.S. states move forward with carbon pricing policies, these pressures are further diminished, suggesting that even the competitiveness pressures identified in this paper may overstate the actual impact on business. Also, as emitters respond to the carbon price over time, by reducing emissions and improving energy efficiency, their carbon costs will fall. Overall, the business community should not perceive carbon pricing as a significant economic threat.

2. Competitiveness pressures should neither preclude nor delay policy action.

It is possible to move forward on policy using targeted support. This support does not require the blanket exemption of vulnerable sectors, which would undermine the policy and increase the burden on the remaining sectors. Instead, cap-and-trade systems—such as those in California and Quebec—can provide limited emissions permits for free based on production or emissions intensity. Experience and economic research suggests that such "output-based allocations" can offset competitiveness pressures (Fischer & Fox, 2004, 2009a; Rivers, 2010). In the case of a carbon tax, the equivalent policy is a rebate to firms based on their production levels (Fischer & Fox, 2009b). In both cases, emitters still have incentives to reduce their GHG emissions but have dampened incentives to reduce their production.[10]

3. Support for vulnerable sectors should be *targeted*.

Providing any free permits generates two challenges for policymakers. First, by treating some firms or sectors differently from others, free permits can be divisive and can undermine the political acceptance of the policy. Second, the more permits are provided for free, the less carbon pricing revenue is generated. Forgoing revenue means having less opportunity for revenue recycling through, for example, reducing existing taxes. These challenges point to the importance of policymakers identifying the *genuine* competitiveness pressures created by the policy, and altering the policy design only to deal with these situations. At the same time, they will need to resist the claims from those entities that might exaggerate their own exposure to such pressures.

4. The process and mechanisms for providing support should be *transparent*.

While only some sectors and firms will face significant competitiveness pressures, *all* firms have incentives to seek additional support from government. A transparent, data-driven approach to identifying competitiveness pressures can help ensure that support is provided only where it is needed to address legitimate competitiveness concerns, rather than relying on the stated needs from firms, whose objectivity may be questioned. This approach can help ensure the credibility of carbon pricing overall, but it can also ensure that the policy is effective in reducing GHG emissions and does so at the lowest possible economic cost.

5. Support to specific sectors should be *temporary*.

Providing transitional support gives emitters time to adjust to policy. But competitiveness pressures are likely to decline over time, as more jurisdictions implement carbon pricing, and as the market works by producing carbon-reducing innovation that emitters can adopt to reduce emissions at lower costs. Providing temporary support for vulnerable firms produces additional incentives for them to develop innovative solutions, but also limits the cost of providing this support. British Columbia, for example, recently provided transitional support to the cement sector in the form of $22 million over three years to address that sector's competitiveness challenges.

6. Any support should be justified by data and analysis.

The analysis in this paper offers a first look at the competitiveness pressures created by carbon pricing in Canadian provinces. Other factors also matter. What is the market structure of the industry, and to what extent can carbon costs be passed on to consumers? How do other policies, such as corporate taxes and resource royalties, affect the carbon costs borne by emitters? How important are the differences in technologies and emissions intensities among the

10 Emitters are still included under the cap—i.e., they are not *exempted*—and so reducing one tonne of CO_2e means they can sell (or avoid purchasing) an additional permit. The *marginal* price of carbon maintains the firms' incentive for reducing emissions. But by increasing a firm's overall profits, providing rebates or free permits based on its output creates an additional incentive for production. Together, the two incentives mean that emitters can benefit by reducing emissions through improved performance rather than by reducing production.

various firms within any given sector? How stringent is the carbon policy in the jurisdictions that represent the relevant external markets for Canadian firms? The detailed data necessary to answer these questions is generally not publicly available and may only be available from businesses themselves.

Implementing an effective and cost-effective carbon pricing policy can generate significant economic and environmental benefits to each province, if the policy is designed well. But some firms and industries will be exposed to genuine competitiveness pressures created by the policy. The provision of special support to specific firms or sectors should not be the default position for policymakers, but rather the exception. In the end, firms and governments need to demonstrate genuine competitiveness pressures to justify creating targeted, transparent, and temporary support measures.

7. Next steps

This report establishes a framework for assessing competitiveness pressures under provincial carbon pricing policies. It finds that competitiveness need not be an obstacle to moving forward with carbon pricing policy, as the policies can be designed to address these challenges. Our next report considers these design solutions in detail. It considers different approaches to recycling carbon pricing revenue back to the provincial economy, including approaches to address competitiveness concerns.

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Provincial carbon pricing and competitiveness pressures: The case of cement trade

Vincent Thivierge[1]

This is Exhibit K
referred to in the Affidavit
of Tom Lesiuk #2
sworn before me this 19th day
of December 2018
A Commissioner for taking Affidavits within British Columbia

November 7th 2017

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ABSTRACT

The impact of unilateral carbon pricing on domestic industry is a central element in current policy debates dealing with mitigation of greenhouse gas emissions. This is especially the case for industries that are both emission-intensive and trade-exposed. A poster child for these vulnerable industries is the cement industry. In this article, we examine the impact of British Columbia's carbon tax on cement trade. We use quarterly data on volumes of imports, exports and net exports of cement between cement producing Canadian provinces, and the US and the World. Through a series of econometric models, results suggest that imports increased as a result of the policy. As a share of average production, estimates point to increased World imports from 3.3 to 9 percent as a share of domestic cement production. This trade effect seems to be driven by substitution between domestic production and imports. The paper also discusses policy options to address these competitiveness pressures in the cement industry.

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Introduction

Concerns over the impact of carbon pricing on domestic industries is an important component of current climate policy debates in Canada. These concerns stem from the *unilateral* implementation of new or more rigorous climate policies by a jurisdiction compared to its trading partners. In Canada, as highlighted by Canada's Ecofiscal Commission (2015a), this situation could be problematic for provincial industries that are simultaneously carbon and trade exposed. While the carbon intensiveness of a specific provinces' electricity grid is an important determinant of the overall risk of a province, an industry that faces carbon competitiveness pressures despite its provincial location is cement manufacturing.

Because of its important carbon footprint and exposure to international trade, cement manufacturing is a poster child for the competitiveness impacts of climate policy on domestic industries. In Canada, the current patchwork of provincial carbon pricing policies has raised concerns by the industry. More precisely, British Columbia's carbon tax is held responsible for the lost of business by British Columbian cement producers. In February 2014, the Cement Association of Canada released a statement about their BC members: "local producers have lost nearly a third of the market share to imports since the inception of the carbon tax in 2008".[1] Similarly, Maclean's magazine also suggested that BC's tax "led to a surge in deliveries of overseas cement".[2]

The objective of this paper is to empirically explore the impacts of BC's carbon tax on cement manufacturing with the help of provincial cement trade data. Conducting this exercise is critical for two reasons. Looking at British Columbia's cement industry can help shed light on the sensitivity of Canada's cement industry to carbon pricing. This is especially important as the stringency of carbon pricing policy is set to converge and increase in Canada, and because of the increased risks of weakened climate policy south of the border. Such information is critical to determine the proper policy response from governments. In the case of BC's carbon tax, the government adopted a temporary rebate program specifically for its cement industry in its 2015 Budget, close to seven years after the implementation of the tax.

Several studies have empirically analyzed the impact of carbon pricing or more broadly environmental regulation on international trade. Using pollution abatement expenditures as a proxy for regulatory stringency, Levinson and Taylor (2008) find modest impacts of environmental regulations on the average industry's trade position. They estimate a one percent increase in pollution abatement costs for US manufacturing industries decreased net exports by 0.064 percent as a share of U.S. value shipped. However, for the 20 industries for which pollution costs increased the most, this estimate translates to more than half of the total increase in trade volume is due to decreased net exports from increased pollution costs.

Using changes in energy prices as a proxy for carbon pricing, Aldy and Pizer (2015) find that a $30 per tonne carbon price in the US would lead to a 10 percent production decline but only less than 2 percent decrease of net exports for energy intensive sectors. Fowlie et al (2016b) use a US firm level dataset to estimates the impact of changes in energy costs on imports, exports and domestic production for different industries. They find that for an industry like cement, a hypothetical domestic US carbon tax of $10 is associated with 20% reduction in exports volumes and increases in imports exceeding 10%.

Rivers and Schaufele (2015a) examine the impact of BC's carbon tax on the province's agricultural trade. Using provincial trade data of agricultural products, they find no evidence of reduced exports or increased imports as a response to the tax. As a relatively less emission-intensive sector, this is not a surprising result for the agricultural sector and consistent with the above studies.

We build on the previous studies in two important ways. First, similarly to Rivers and Schaufele (2015a), we examine the impact of carbon pricing on the trade position of an industry using a stand-alone carbon tax within the province of BC as opposed to relying on proxy variables. Second, we look at the impact of the policy on one of the most emission-intensive and trade-exposed industry in the province.

Results from this paper suggest that the carbon tax affected British Columbia's cement industry's trade position. We explore a number of regression models that suggest the policy increased imports and reduced net exports. Results suggests that as a share of average production, imports from the World increased by 3.3 to 9 percent and net exports from the World reduced by 19 percent. Empirical investigation suggests this trade effect is driven by substitution between domestic production and imports. Such a result in principle justifies British Columbia's tax rebate policy to support its cement industry.

The paper is separated into five sections. Section 1 provides an overview of Canadian cement manufacturing and how that relates to carbon pricing policy. Section 2 describes the intuition of the empirical analysis used in the paper. Section 3 presents the data and discusses the econometric models and results. Section 4 presents the important factors governments should consider when designing support policies and the final section provides concluding remarks.

Section 1: Thinking about the cement industry and carbon pricing

Manufacturing cement is an energy and greenhouse gas emission intensive process. Coupled with the fact that cement is increasingly shipped internationally makes this industry one of the most exposed to carbon competitiveness risks (Miller et al, 2017). This section explores the links between the industry's characteristics and carbon pricing.

Overview of the cement industry

Cement is the primary ingredient of concrete, a key construction material. It is used for the construction of residential and non-residential buildings, and also for bridges, roads and sewage pipes.

To produce cement, plants first heat raw materials (mostly limestone, silica, alumina and iron) in kilns at temperatures up to 1500 degrees Celsius. This produces cement's main input; clinkers. Clinkers are then grinded with otber additives (such as gypsum and limestone) to create cement.

The kiln process makes cement manufacturing energy-intensive. The production of clinkers accounts for 90 percent of the cement's industry's energy consumption. Heating up the kiln relies heavily on burning carbon-intensive fossil fuels, such as coal and petroleum coke. For the past two decades, the share of fossil fuels accounted for over 75% of the industry's energy share (CIEEDAC, 2016).[3]

Burning heavy fuels translates to an important carbon footprint. For every tonne of cement produced in Canada, nearly a tonne of GHG is emitted. However, more than half of the industry's GHG emissions are actually process emissions. They are a by-product of the chemical reaction of limestone turning into clinkers. The remainder—about 40% of GHG emissions— are from burning of fossil fuels, also referred to as combustion emissions. The distinction of process and combustion emissions is important since BC's carbon tax only applies to combustion emissions.

Cement markets in Canada

In 2013, there were 17 operational cement plants in Canada: seven plants in Ontario, four in Quebec, three in BC, and two in Alberta and one in Nova Scotia.

Because of its low value to weight ratio, cement is a costly product to transport over roads. As such, the industry has often been characterized as serving regional markets. In the US, an estimated 80% to 90% of domestically produced cement is trucked less than 200 miles (or 321 kilometers) (Miller et al, 2017). Coastal cement plants can face substantially more international import competition compared to landlocked cement plant. A coastal regional market such as Seattle has an import market share of 65%, whereas an inland market such as Denver's has a null import share (Fowlie et al, 2016a).

In Canada, while regional market data is not available, provincial level import market share provide a similar but less extreme picture. In 2011, BC's import market share was slightly below 30 percent, the Prairies and Ontario close to 20 percent and Quebec's below 15 percent. This could be explained by the fact that good inland navigable waterways, such as the Great Lakes, can also increase competition for local producers.

British Columbia's carbon tax

By putting a price on GHG emissions, carbon pricing has the potential to increase the costs of manufacturing cement, both in terms of its combustion and process emissions. In the case of BC's carbon tax, it only applies to the GHG content of fossil fuels. As such, the policy can increase the costs cement industry energy inputs, such as coal, petroleum coke and natural gas.

Table 1 provides the emission intensity of Canada's cement industry.[4] Multiplying row one with the share of combustion emission gives the combustion based emission intensity of cement. Combining the combustion based emission intensity with the per tonne of GHG carbon tax gives the per comment tonne cost of the tax. Table 2 provides the carbon costs per tonne of cement produced for carbon pricing policies in BC, Alberta and Quebec.

[insert Table 1 here]

[insert Table 2 here]

The cost of BC's policy in 2012 is more than 15 times the stringency of Alberta's policy and nearly 10 times Quebec's. Using a manufacturing level dataset in Alberta, Rajagopal (2014) finds no evidence of an effect of Alberta's carbon pricing policy on emissions or emission intensity, including the cement manufacturing. As such, the main focus of the empirical analysis is identifying the impact of BC's carbon tax. An alternative approach is to model all provincial carbon pricing policies in Canada. As reported in Table 8 in the Appendix, including all carbon prices does not substantially change the main estimates.

Given an average price of cement of CAD$100 per tonne (Miller et al, 2017), BC's 2012 carbon costs translate to about 10% of the products' price. These costs are a significant portion of the finished products' price. For comparison, BC's carbon tax is equivalent to slightly less than 7% of gasoline price at the pump (Lawley and Thivierge, 2018).

Cement manufacturing exposure to competitiveness pressures

Given the relative stringency of BC's carbon tax compared to its international cement trading partners, such as the USA and Asian countries, it could cause reduced net exports. In the economics literature, this is known as the pollution haven effect (PHE).

The reduction of net exports through increased foreign imports can cause a related environmental problem which is emission leakage. The consequence of leakage is that the relocation of economic activity does not change global GHG emissions, as they are simply emitted elsewhere. This situation reduces the effectiveness of domestic policy. In the worst-case scenario, if foreign production methods are dirtier than domestic ones, leakage could lead to net global increases in emissions.

It is important to situate the study within the broad concept of competitiveness (for an extensive definition of competitiveness, see Canada's Ecofiscal Commission (2015a)). Depending on the level, whether at the firm or sector level, competitiveness refers to different effects. At the industry level, competitiveness often refers to the ability of one countries' industry to perform in international trade, measured for example in net exports or investment flows (Dechezleprêtre and Sato, 2017).

Section 2: A first look into the impact of BC's carbon tax

Determining whether a carbon tax lead to changes in trade is an empirical question. BC's carbon tax lends itself well to this challenge. The province implemented quickly a broad and stringent policy (Rivers and Schaufele, 2015a). Researchers can exploit provincial-specific changes to identify the impact of the policy separately from other economic trends.

This approach of exploiting the carbon tax as a natural experiment has been used by Canadian economists to look at the impact of the policy on multiple BC outcomes: gasoline consumption (Rivers and Schaufele, 2015b; Antweiler and Gulati, 2016; Lawley and Thivierge, 2018), vehicle purchases (Antweiler and Gulati, 2016), jobs (Yamazaki, 2017) and closest to this paper, on agricultural trade (Rivers and Schaufele, 2015a).

Our analysis is restricted to the four larger cement producing provinces: BC, Alberta, Ontario and Quebec. While the Atlantic provinces have cement producing capacity, they are left out of the sample, because of their relative small size, the shutting down of a plant in the sample and lack of data.

[insert Table 3 here]

Table 3 provides summary statistics of the cement industries in the four provinces. All provinces are net exporters of cement, but only marginally so for Alberta. For provinces like BC and Ontario, they export on average more than seven size times the amount they import. In terms of domestic production, Ontario has by far the largest cement industry. Quebec is second, and then BC. Production data for Alberta is unavailable.

Graphical analysis

The empirical approach presented above can be explained through graphical analysis. Comparing the trends of British Columbia cement imports or exports compared to the other cement provinces before and after the implementation of the tax can provide insight of whether there are reasons to believe there has been a policy impact. Divergence between BC and the other provinces after the tax was implemented would suggest an impact.

Figures 1 plots yearly import of cement in the four provinces from 1988 to 2013. The left panel presents total imports from all countries, while the right panel provides the subset of imports from the USA. The blue dotted line shows the implementation date of BC's carbon tax. It is evident from both panels that most imports are from the US for all four provinces but Quebec.

From both panels, imports in BC have increased following the implementation of the policy. However, two points suggest caution in assigning this impact to the carbon tax. First, imports were increasing in the other three provinces. This could be explained by the global recession of 2008 which happened around the same time as the implementation of the tax, making the identification of the tax's impact separately from the recession difficult graphically. Also, imports were increasing in BC prior to the policy.

[insert Figure 1 here]

Figure 2 presents yearly exports of cement for the four provinces. Panel A for provincial exports to the world and panel B, exports to the USA. Even more starkly than for Figure 1, nearly all provincial exports are destined to the USA.

Similarly to Figure 1, for the years before and after the tax, exports follow in all four provinces similar trends. Exports were falling prior to the tax and increasing following the tax, with the slight exception of Alberta.[5]

[insert Figure 2 here]

While this graphical analysis seems to suggest that the tax might not have led to increases in BC's imports or reduction in exports of cement, such analysis does not have the rigorous statistical basis required to answer the question. As such, the next sections present the data and results from econometric modeling.

Section 3: Econometric modeling and results

In order to more formally assess the impact of BC's carbon tax on cement trade, the next section relies on econometric modeling. The models look at changes in trade data in BC and other major cement producing provinces while controlling for important factors. Specifically, we estimate the impact of the carbon tax using two models.

The first is the log-linear model used in Rivers and Schaufele (2015a):

$$log\left(Y_{p,y,q}\right) = \beta_1\tau_{p,y,q} + X_{p,y,q}\Theta_1 + \delta_{1p} + \gamma_{1p} + \zeta_{1q} + \varepsilon_{p,y,q} \qquad (1)$$

The second is an adaptation of the specification used in Levinson and Taylor (2008):

$$\left(Y_{p,y,q}/Q_{p,y}\right) = \beta_2\tau_{p,y,q} + X_{p,y,q}\Theta_2 + \delta_{2p} + \gamma_{2p} + \zeta_{2q} + \omega_{p,y,q} \qquad (2)$$

where $Y_{p,y,q}$ is the quantity in tonnes of cement exports, imports or net exports in province p, year y and quarter q; $Q_{p,y}$is the yearly provincial cement production in tonnes; $\tau_{p,y,q}$ is the per tonne of cement carbon tax if the cement industry is in BC; $X_{p,y,q}$is a vector of provincial economic and construction variables; δ_p, γ_y, ζ_q are province, year and quarter fixed effects, respectively; and $\varepsilon_{p,y,q}$ and $\omega_{p,y,q}$ error terms.

Because the sample only includes four provinces, clustering of the error terms by province would not be appropriate. As discussed in Cameron et al (2008), problems arise when trying to conduct statistical inference with a small number of clusters. The calculated standard errors will lack the required asymptotic properties. As such, Driscoll-Kraay standard errors are employed as an alternative to clustering. Driscoll-Kraay standard errors exhibit better asymptotic properties when cross-sectional dimension is small, such as a small number of provinces, and the time dimension is large (Hoechle, 2007).[6]

From models (1) and (2), we are primarily interested in β_1 and β_2, which give us estimates of the impact of the carbon tax. β_1 represent the percentage change in imports or exports for a one dollar increase in carbon costs. Because model (1) takes the natural logarithm of the dependent variable, we only look at imports and exports for that model. Net exports can be either positive or negative and as such this variable cannot be logged. In model (2), for imports, exports and net exports, β_2 represents the percent change of trade as a share of cement production from a one dollar increase in carbon costs.

Coefficients of the covariates for model (1) can be interpreted as one percent change in the variable leads to a Θ_1 percent change in trade. Similarly, for (2), Θ_2 represent the percent change of trade as a share of cement production from a one percent increase in the covariate.

The province and time fixed effects are included in models to account for observed and unobserved differences affecting provincial cement industries. Province fixed effects account for constant differences between province cement industries, such as market access and industry costs. It controls for provincial-industry differences, such as differences in industry costs, structure and market access. For example, it accounts for BC's cement plants higher trade exposure to Asian countries. The quarter fixed effect control for seasonality in cement trade. The year fixed effects account for factors such as changes in the general economic context in Canada, such as recessions, exchange rates, commodity prices and federal trade policy. These time fixed effects account for changes that affect the Canadian cement industry as a whole.

The control variables included in the models account for factor ignored by the fixed effects that might influence cement trade, such as changes in provincial economic or construction activity. The section below presents in more detail the dataset and the control variables.

Data

The outcome variables, the quantity of provincial cement imports and exports, are pulled from Statistics Canada's Canadian International Trade Database. The variables' time frame spans 1988 to 2013. They are at the quarterly frequency to increase observations and variation in the data.

Yearly provincial cement production data is provided by Natural Resource Canada's mineral yearbook. Because of the privacy concerns over of provincial level industry data in Canada, cement production data is only publicly available for BC, Quebec and Ontario and from 1992 to 2011.

We include two provincial and quarterly varying control variables to account for differential rates of demand for cement in the four provinces. From Statistics Canada, we include provincial quarterly unemployment rates. Also from Statistics Canada, we have the number of residential building starts by province and quarter. Expected impact is that increased local demand in cement would increase imports and reduce exports. The inclusion of unemployment rates and a construction activity variable is akin to the covariates employed in Fowlie et al (2016a).

Results

In order to build confidence on our results, we estimate several econometric models. These differing scenarios are intended to measure the sensitivity of the results with respect to varying assumptions about model choices. The primary objective of all models is assessing whether BC's carbon tax led to significant changes in its industry's cement trade position.

To address the importance of the rise in overseas cement imports, we analyze trade separately for the US and the World. World imports might be more sensitive to carbon costs than US imports if indeed the policy is leading to increase overseas imports. Each result table presents the effect of the carbon tax for six outcome variables: US imports, World imports, US exports, World exports, US net exports and World net exports.[7]

Using coefficients for model (1) and (2), Table 6 at the end of the section provides estimates of the impact of BC's $30 per tonne carbon tax on imports and net exports.

Table 4 reports results from model (1) accounting for all fixed differences between provincial cement industries, yearly changes to the Canadian industry as a whole and two provincial time varying control variable: quarterly unemployed rate and residential construction starts.

All the coefficients of the carbon tax have the expected sign, i.e. increase in imports, and reduction in exports and net exports. However, only the effect of the carbon tax for both US and World imports in BC is significant. A one-dollar increase in the per cement tonne carbon cost relates to a 3.1 percent increase in the quantity of US imports and a greater increase of World imports of 4 percent. The carbon tax coefficients for exports have the expect signs, but are not significant. While not included explicitly, it is expected that these results translate to reductions in net exports.

[insert Table 4 here]

The coefficients for residential starts make intuitive sense for imports but not exports. For imports, coefficients are positive and significant. Estimates suggest that both US and World imports, a one percent increase in residential starts results in about 0.65 percent increase in cement imports. Counter to economic intuition, a one percent increase in residential starts also is significantly associated with increase exports of 0.3 percent.[8] On the other hand, the sign of the coefficient for unemployment make potentially more economic sense. Increases in provincial unemployment lead to reduction in imports and increase exports of domestic production abroad. However, only the export coefficients are significant. A one percent increase in unemployment rate leads to increased export of 0.36 percent.

Table 5 presents the results from model (2), which normalizes the trade variables by domestic cement production. This controls for the differences in sizes of cement industry by province (Levinson and

Taylor, 2008). However, given the lack of publicly available provincial cement production data, the sample drops Alberta and is restricted to 1992 to 2011.[9]

Similar to the results from model (1), these estimates suggest that the carbon tax led to increases in imports. Model (2) also confirms the intuition of the results from model (1) as they suggest significant reductions in net exports. A one-dollar increase in carbon cost is linked to a 0.4 percent and 0.9 percent increase of respectively US and World imports as a share of production. A one-dollar increase in costs reduces net exports to the US as share of production by 1.3 percent and for net exports to the World by 1.8 percent.

[insert Table 5 here]

Results in Tables 4 and 5 provide evidence for a pollution haven's effect for BC's cement industry and the carbon tax. The models suggest that the policy is linked to increased imports and, decreased net exports. Results also point qualitatively to larger impacts for World trade as opposed to US trade. The next sub-section compares the magnitudes of the impacts for both models.

Comparing the magnitude of the results

Because of the transformations of the outcome variables, the coefficients from Tables 4 and 5 are not directly comparable. As such, using coefficient of the carbon tax from each table, Table 6 provides estimates of the impact of BC's carbon tax on the cement industry for imports and net exports as a share of the industry's production. Exports are not presented, as the carbon tax coefficients are never statistically different than zero.

[insert Table 6 here]

Model (1) and (2) suggest that the $30 per tonne carbon tax increased US imports by 3.3 to 4 percent as a share of average BC cement production. Estimates for World import they increased by 4.3 to 9 percent as a share of production as a result of the policy. To put these numbers in context, using the estimates of residential starts in Table 5, this is equivalent to the suggested increases in US and World cement imports from a 1.2 to 2.7 percent increase in residential construction starts in BC.

For net exports to the US, estimates suggest that the BC carbon tax led to an impact of 13 percent reduction as a share of average cement production. Results suggest net exports to the World reduced as a result of the province's carbon pricing policy by 18 percent. These greater impacts are likely driven by the combination of the non-significant but negative coefficients on exports with the significant and positive import coefficients.

What is driving this trade effect?

Looking at the impact of the carbon tax on changes in domestic use of cement can provide insight into the sources of the effect on trade. [10] This has implication for what the effect means for carbon leakage and the competitiveness pressures. If BC's carbon tax did not change domestic use, this would suggest substitution between domestic production and imports. Such a substitution would imply carbon leakage if the production methods abroad are more GHG intensive as opposed to domestic production. However, if domestic use reduces as a consequence of the carbon tax, then this domestic reduction in use, or GHG emissions, translates to carbon leakage through the increased imports.

Table 7 looks at the effect of BC's carbon tax on domestic cement use both in levels in column (1) and (2) and as a log-linear model in column (3). Results suggest that the carbon tax did not lead to changes in domestic use of cement. This would imply that carbon leakage impacts of the carbon tax on cement are likely to be limited.

[insert Table 7 here]

However, the finding of imports increases and net exports decreases does provide evidence that the policy did have competitiveness impacts on the industry. As one of the more carbon-intensive and trade-exposed industry in Canada, these results can also be interpreted as upper-bound estimates of what can be expected as trade impacts in industries that face carbon competitiveness pressures.

For BC's cement industry, these trade effects justify governmental intervention to relieve this competitive disadvantage. The next section explores the policy space for competitiveness support policy for the cement industry.

Section 4: Design of competitiveness support policies

As one of the more trade-exposed and emission-intensive industry, the econometric modeling suggests a $30 per tonne combustion-based carbon tax in the cement industry can led to increased trade competitiveness.

In such context, government support can be provided to alleviate such pressures. For a government looking to reduce domestic greenhouse gas emissions with carbon pricing, reducing competitiveness pressures for a sector or industry becomes an additional policy goal. The objective of carbon pricing is to reduce emissions-cost effectively. Economic theory suggests employing additional policies to address additional policy goals as opposed to exempting an industry from the initial policy (Rivers and Schaufele, 2015a). Exempting an industry from carbon pricing dampens the policy's objective. In the case of BC, exempting the cement industry reduces the coverage of its carbon tax and might prevent cost-effective emission reductions.

Effective industry competitiveness support policy can take the form forgone carbon revenue by governments through free permits allocations in a cap-and-trade or rebates under a carbon tax (Fischer and Fox, 2004; Canada's Ecofiscal Commission, 2016). Under a cap-and-trade system, free permits are allocated per unit of production based on an industry-specific emission intensity target. The equivalent rebate under a carbon tax would use revenue generated by the tax to provide a per unit of production subsidy based on the same industry-specific emission intensity target.

By maintaining carbon pricing coverage, these support policies keep the marginal incentives to reduce GHG emissions, while limiting the incentive for firms to reduce GHGs through reduced production or relocation of plants. If a firm covered by the support policy wants to emit an additional tonne of GHGs, it will either pay the tax or purchase a permit at the going carbon price. The support policy provides an implicit output subsidy for the firm to maintain or increase its production levels. This depends on the levels of the firm's emission intensity with respect to the emission intensity the target of the support policy.

The level of the industry specific emission intensity target is key to determining which type of firm will be rewarded. If the level is too low, it will not provide incentive for more efficient production as all firms will be rewarded with an output subsidy or free permits. A rule of thumb is to set the target at the level of "best available technology" in an industry. Firms who meet or exceed that target are rewarded, whereas the technological laggards will have to pay more of the carbon tax or purchase additional permits. Also, periodic revisions of emissions intensity targets based on recent technological advances can provide incentives for continued innovations (Antweiler, 2016).

There are trade-offs to such government support. Namely, competitiveness support policies might result in smaller overall GHG reduction compared to a situation without them, by keeping production higher in the compensated sectors. Also, governments providing such support to a sector runs the risk of increasing lobbying efforts by other sectors to receive compensation that might not be needed (Canada's Ecofiscal Commission, 2016).

In its 2015 Budget, British Columbia adopted a temporary rebate program for its cement industry. The program will offer subsidies up to $27 million to cement producers that meet or exceed emission intensity targets between 2015 to 2020. While the specific details of the program are unknown, such as the emission intensity benchmark, the principles of the program appear to respect the above criteria.

Section 5: Summary and concluding remarks

In this study, we analyzed the impact of BC's carbon tax on cement trade. Our results suggest that the policy led to increased imports and reduced net exports. We find that the $30 per tonne carbon tax in lead to increased imports from the World of 3.3 to 9 percent and reductions and net exports from the World by 19 percent as a share of domestic production. The source of this effect is driven by substitution between domestic production and imports. While this substitution effect implies limited carbon leakage, it does suggest the necessity for support policy by the BC government.

BC's government has recently put in place a tax rebate policy for its cement sector; however, it is too early to analyze its key details, such as the level and path of its emission intensity benchmark. Also, while the BC government is developing an industry-specific competitiveness support policy, it is still exempting process emissions for the cement industry and all sector of its economy from its carbon tax. The implementation of its support policy to the cement industry, and extending it to other industries that face substantial carbon competitiveness pressures, is an opportunity for the province to include process emissions under its carbon pricing policy.

Notes

[1] Cement Association of Canada (2014), B.C.'s Jobs Plan Should Support B.C. Cement Industry. Retrieved from: http://www.cement.ca/en/News-Releases/B-C-s-Jobs-Plan-Should-Support-B-C-Cement-Industry.html
[2] Maclean's (2016), Canada's cement industry is crumbling. Retrieved from: http://www.macleans.ca/economy/business/canadas-cement-industry-is-crumbling/
[3] The use of alternative fuels, such as waste and wood fuels is limited.
[4] Data on the share of combustion emissions is only publicly available at the national industry level.
[5] This graphical analysis with similar conclusions can be performed on additional variables of interest included in the appendix, such as net exports and domestic production.
[6] More importantly, when using robust, cluster or Driscoll-Kraay standard errors, the significance of the results do not qualitatively change.
[7] A better approach to test the sensitivity of the effect of carbon tax on trade by trading partner would be to look at either the US or the World minus the US. However, as shown in Figure 1 and 2, most of cement provincial trade is with the US. As such, World trade minus the US includes quarterly null values which cannot be used in the above models.
[8] Most importantly, when removing the variable, it doesn't change the sign of the carbon tax coefficients.
[9] The regressions in Table 3 were ran under this reduced sample, and while significance drops, the sign and magnitude of coefficients are similar.
[10] Domestic use is defined as domestic production minus exports plus imports.

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Table 1: Greenhouse gas emission intensity of the Canadian cement industry

Year	2007	2008	2009	2010	2011	2012
GHG/output	0.90	0.92	0.96	0.92	0.93	0.87
Share of combustion emissions	42%	44%	46%	44%	45%	40%
Combustion based GHG/output	0.38	0.40	0.45	0.40	0.42	0.35

Source: CIEEDAC (2016)

Table 2: Provincial carbon pricing policy carbon cost per tonne of cement

Province	Policy cost metric	2007	2008	2009	2010	2011	2012
B.C	$/tonne of GHG	-	$10.00	$15.00	$20.00	$25.00	$30.00
B.C	**$/tonne of cement**	**-**	**$3.99**	**$6.70**	**$8.07**	**$10.40**	**$10.49**
Alberta	$/tonne of GHG	$1.80	$1.80	$1.80	$1.80	$1.80	$1.80
Albert	$/tonne of cement	$0.68	$0.72	$0.80	$0.73	$0.75	$0.63
Quebec	$/tonne of GHG	$4.00	$3.90	$4.00	$4.20	$4.30	$4.30
Quebec	$/tonne of cement	$1.52	$1.56	$1.79	$1.70	$1.79	$1.50

Source: Canada's Ecofiscal Commission (2015b)

Table 3: Summary statistics, 1988 to 2013 (in thousands)

	B.C.		**Alberta**		**Ontario**		**Quebec**	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Imports	144	81	227	112	326	102	143	97
Exports	1023	368	237	106	2527	653	576	259
Net exports	878	402	10	141	2201	661	433	265
Production	1925	404	N.A.	N.A.	5332	972	2742	278
Residential starts	29	8	27	11	66	16	41	11
Unemployment	7.8%	1.6%	6.0%	1.8%	7.6%	1.6%	9.6%	1.8%

Source: Author's calculations, Statistics Canada (2017) and Environment Climate Change Canada (2015)
Notes: Imports, exports, net exports and productions are in thousands of tonnes. S.D. stands for "standard deviation" and N.A. for "not available".

Table 4: Effect of B.C.'s carbon tax on trade

	(1) log(Imports from U.S.)	(2) log(Imports from World)	(3) log(Exports to U.S.)	(4) log(Exports to World)
B.C. carbon tax	0.031* (0.017)	0.040** (0.017)	-0.003 (0.011)	-0.002 (0.011)
Log(Residential starts)	0.651*** (0.132)	0.647*** (0.152)	0.285*** (0.109)	0.291*** (0.110)
Log(Unemployment rate)	-0.186 (0.228)	-0.278 (0.278)	0.361** (0.144)	0.362** (0.147)
Number of observations	416	416	416	416
Adjusted R^2	0.63	0.49	0.58	0.58

Notes: All regressions include province, year and quarter fixed effects. Driscoll and Kraay standard errors are in parentheses. *p<0.1; **p<0.05; ***p<0.01

Table 5: Effect of B.C.'s carbon tax on trade as a share of production

	(1) Imports from U.S. (%)	(2) Imports from World (%)	(3) Exports to U.S. (%)	(4) Exports to World (%)	(5) Net exports to U.S. (%)	(6) Net exports to World (%)
B.C. carbon tax	0.004*** (0.002)	0.009*** (0.002)	-0.009 (0.006)	-0.009 (0.006)	-0.013* (0.007)	-0.018*** (0.007)
Log(Residential starts)	0.028*** (0.005)	0.033*** (0.009)	0.083* (0.043)	0.086** (0.042)	0.055 (0.040)	0.053 (0.039)
Log(Unemployment rate)	0.033*** (0.011)	-0.012 (0.023)	0.351** (0.087)	0.358** (0.085)	0.318*** (0.083)	0.370*** (0.077)
Number of observations	240	240	240	240	240	240
Adjusted R^2	0.47	0.46	0.57	0.58	0.57	0.56

Notes: The sample for the above regressions is restricted to 1992 to 2011 and drops Alberta. All regressions include province, year and quarter fixed effects. Driscoll and Kraay standard errors are in parentheses. *p<0.1; **p<0.05; ***p<0.01

Table 6: Summary of the effect of B.C.'s carbon tax on trade as a share of production

	(1) Imports from U.S.	(2) Imports from World	(3) Net exports to U.S.)	(4) Net exports to World
Model (1)	3.3%	4.3%	-	-
Model (2)	4.0%	9.0%	13.0%	18.0%

Notes: For the model (1), the impact is estimated as the related carbon tax coefficient from Table 4, multiplied by the total carbon costs per tonne of cement, time the average volume of trade, over the average cement production. For model (2), it is the related carbon tax coefficient from Table 5 time the total carbon cost per tonne of cement.

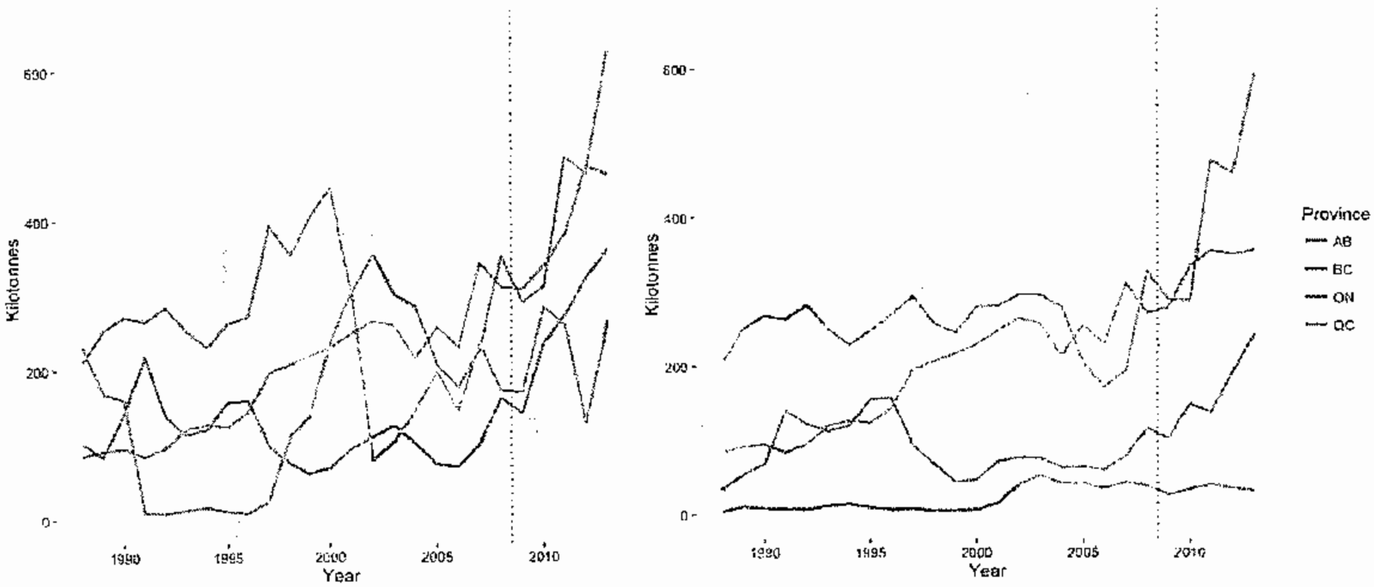
Table 7: Effect of BC's carbon tax on domestic cement use

	(1) Domestic use	(2) Domestic use	(3) log(Domestic use)
B.C. carbon tax	0.001	0.0004	0.025
	(0.004)	(0.004)	(0.017)
Log(Residential starts)	0.002	0.003	-0.092
	(0.045)	(0.047)	(0.147)
Log(Unemployment rate)	-0.264***	-0.273***	-0.920***
	(0.079)	(0.086)	(0.297)
Number of observations	240	228	228
Adjusted R^2	0.48	0.48	0.45

Notes: The sample for the above regressions is restricted to 1992 to 2011 and drops Alberta. Columns (2) and (3) also drop the year 1998. All regressions include province, year and quarter fixed effects. Driscoll and Kraay standard errors are in parentheses. *p<0.1; **p<0.05; ***p<0.01

Figure 1: Yearly imports of cement by Provinces (Kilotonnes)

Panel A: Imports from World **Panel B: Imports from USA**



Source: Canadian International Trade Merchandise Database

Figure 2: Yearly exports of cement by Provinces (Kilotonnes)

Panel A: Exports to World **Panel B: Exports to**

USA

Source: Canadian International Trade Merchandise Database

Appendix: Modelling of all provincial carbon pricing policies and additional figures

Table 8 estimates the impact of carbon prices in BC, Alberta and Quebec on imports and net exports using model (1). The covariates and fixed effects included are the same as in the regressions presented in Table 4, namely provincial, year and quarter fixed effects and logged quarter unemployment rate and the number of residential construction starts. The signs and magnitudes of the effects of carbon pricing on imports and exports are qualitatively similar to the main estimates reported in Table 4. The coefficients on imports are also estimated with greater precision in Table 8. These results provide confidence on the main regressions which only include BC's carbon tax.

Table 8: Effect of provincial carbon pricing on trade

	(1) log(Imports from U.S.)	(2) log(Imports from World)	(3) log(Exports to U.S.)	(4) log(Exports to World)
Carbon price	0.041**	0.055***	-0.008	-0.007
	(0.017)	(0.015)	(0.010)	(0.010)
Log(Residential starts)	0.658***	0.658***	0.280**	0.286***
	(0.130)	(0.154)	(0.109)	(0.110)
Log(Unemployment rate)	-0.156	-0.235	0.350**	0.352**
	(0.227)	(0.274)	(0.146)	(0.149)
Number of observations	416	416	416	416
Adjusted R^2	0.64	0.49	0.58	0.58

Notes: All regressions include province, year and quarter fixed effects. Driscoll and Kraay standard errors are in parentheses. *p<0.1; **p<0.05; ***p<0.01

Figures 3 and 4 present respectively net exports and domestic production of cement for the four provinces. Alberta is not included in Figure 4 since no domestic production data is publicly available. Similar to the graphical analysis presented in the main text, there is no apparent diverging trends between BC and the other provinces before and after the carbon tax's implementation date.

Figure 3: Yearly net exports of cement by Provinces (Kilotonnes)

Panel A: Net exports from World **Panel B: Net exports from USA**

Figure 4: Yearly domestic cement production by Provinces (Kilotonnes)

Court of Appeal File No. C65807

COURT OF APPEAL FOR ONTARIO

IN THE MATTER OF A REFERENCE to the Court of Appeal pursuant to section 8 of the *Courts of Justice Act*, RSO 1990, c. C. 34, by Order-in-Council 1014/2018 respecting the constitutionality of the *Greenhouse Gas Pollution Pricing Act*, Part 5 of the *Budget Implementation Act*, *No. 1*, SC 2018, c. 12

AFFIDAVIT

I, June Parker, Legal Assistant, of 1001 Douglas Street, in the City of Victoria, in the Province of British Columbia, MAKE OATH AND SAY *(or* AFFIRM*)*:

1. Attached hereto and marked Exhibit "A" to this my affidavit is a copy of the article by William Baumol titled "On Taxation and the Control of Externalities" 62: 3 *Am. Econ. Rev.* 307 (1972).
2. Attached hereto and marked Exhibit "B" to this my affidavit is a copy of the article by Maureen Cooper and Wallace Oates titled "Environmental Economics: A Survey" 30 *j. of Econ Lit.* 675 (1992).
3. Attached hereto and marked Exhibit "C" to this my affidavit is a copy of the article by Martin Weitzman titled "Prices vs. Quantities" 41(4) *Rev. Econ Stud.* 477 (1974).
4. Attached hereto and marked Exhibit "D" to this my affidavit is a copy of the article by William Nordhaus titled "Economic aspects of global warming in a post-Copenhagen environment" 107 (26) *PNAS* (2010).
5. Attached hereto and marked Exhibit "E" to this my affidavit is a copy of the article by Wallace Oates and Robert Schwab titled "Economic Competition Among Jurisdictions: Efficiency Enhancing or Distortion Inducing" 35 *J. of Pub. Econ 333* (1988).
6. Attached hereto and marked Exhibit "F" to this my affidavit is a copy of the article by Roland Magnusson titled "Efficiency of Non-Cooperative Emission Taxes in Perfectly Competitive Markets" *Finnish Economic Papers* (2010)

SWORN BEFORE ME)
at Victoria., British Columbia)
on the 11 day of ~~December~~ January, ~~2018~~ 2019.)
)
)
A commissioner for taking)
affidavits for British Columbia)

John M. Tuck
Barrister & Solicitor
Ministry of Justice
Legal Services Branch
PO Box 9280 Stn Prov Govt
1001 Douglas Street
Victoria, BC V8W 9J7

June Parker

This is Exhibit A
referred to in the Affidavit
of JUNE PARKER
sworn before me this 17 day
of DECEMBER 2018

A Commissioner for taking Affidavits within British Columbia

On Taxation and the Control of Externalities

By WILLIAM J. BAUMOL*

It is ironic that just at the moment when the Pigouvian tradition has some hope of acceptance in application it should find itself under a cloud in the theoretical literature. James Buchanan has argued that its recommended taxes and subsidies may even increase resource misallocation in the presence of monopoly. Otto Davis and Andrew Whinston (1962) have, in effect, raised doubts about its applicability in the presence of oligopoly. And Ronald Coase has asserted that the tradition has not selected the correct taxation principle for the elimination of externalities, and may not even have chosen the right individuals to tax or to subsidize. In this paper I will suggest that these authors have led the discussion in our profession to focus on the wrong difficulties. In doing so they have, albeit inadvertently, drawn attention away from some of the most important limitations of the Pigouvian prescription as an instrument of policy and from consideration of the means that might prove effective in practice.

The main purpose of the paper is to show that, taken on its own grounds, the conclusions of the Pigouvian tradition are, in fact, impeccable. Despite the various criticisms that have been raised against it in the large numbers case, which is of primary importance in reality and to which Pigou's analysis directs itself, his tax-subsidy programs are generally those required for an optimal allocation of resources. Moreover, I will attempt to show that where an externality is (like the usual pollution problem) of the public goods variety, neither compensation to nor taxation of those who are affected by it is compatible with optimal resource allocation. Pigouvian taxes (subsidies) upon the generator of the externality are all that is required.

However, as is well known, the Pigouvian proposals suffer from a number of serious shortcomings as operational criteria when one seeks to implement them precisely as they emerge from the theory. I therefore discuss a modified approach that recommends itself more for its promise of effectiveness, than its theoretical nicety. It consists of two basic steps: the setting of standards, more or less arbitrarily, of levels of pollution, congestion and the like, that are considered to be tolerable, and the design of taxes and effluent charges whose rates are shown by experience to be sufficient to achieve the selected standards of acceptability. Such a system of charges will, at least in principle, effect any preselected reduction in,

* Professor of economics, Princeton University and New York University. I would like to express my gratitude to the National Science Foundation whose assistance helped materially in the completion of the paper and to my colleagues James Litvack, Wallace Oates, and David Bradford, to my students Mark Gaudry and Bryan Boulier, and to Peter Bohm, James Buchanan, Ronald Coase, Karl Göran Mäler, Herbert Mohring, and Ralph Turvey who have given me many very helpful suggestions, and saved me from a number of serious errors. Mohring and J. Hayden Boyd have written an extremely illuminating paper dealing, among other relevant matters, with the portions of the Coase-Buchanan-Turvey arguments in the case where the polluters and their victims "can and do negotiate." Since the present paper concerns itself only with the "relevant" large numbers case where there is no negotiation, it deliberately makes no attempt to consider the interesting negotiation case examined so helpfully by Mohring and Boyd.

say, the pollution content of our rivers, at minimum cost to society. It automatically achieves an efficient allocation of the required reduction in emissions among the offending firms *even if they are neither pure competitors nor profit maximizers*. Thus, a persuasive case can be made for the use of taxes and subsidies to control externalities, even if they will not produce an optimal allocation of resources in the complex world of reality.

I. The Coase Argument in the Case Without Negotiation

Recommendations designed for the competitive case can clearly run into difficulties in the presence of monopolistic elements. Buchanan reminds us that, if a polluting monopolistic industry already restricts the outputs of its products below their competitive levels, the imposition of an effluent charge to restrict output still further is hardly likely to be appropriate. And Davis and Whinston (1962) show for the case of externalities under oligopoly that it is rather difficult to come up with an ideal set of taxes since in the small numbers case just about anything is possible by way of pricing and output levels. However, these arguments have little direct bearing on the Pigouvian analysis because it is couched entirely in terms of pure competition (on this see Stanislaw Wellicz' illuminating discussion), which, in view of the large numbers involved in virtually all of the externalities problems that worry us today, is entirely apropos.

Coase's arguments, buttressed by impressive legal erudition, are less easily dealt with. He offers us a number of illuminating observations, among them the interesting point (see his Section IV) that (in the relatively unimportant cases) where only a small number of decision makers is involved, a process of voluntary bargaining and side payments among those concerned by an externality may produce an optimal allocation of resources, even in the absence of liability for damage. This implies that where small numbers are involved, the imposition of a "corrective" Pigouvian tax may be too much of a good thing—it can produce a misallocation rather than eliminating it.

Coase suggests, however, that even in cases where there is no negotiation among the parties affected by an externality the Pigouvian taxes and subsidies may be the wrong remedy—that they may only modify the character of the misallocation of resources. Coase's central argument appears to be the following: Every social cost is inherently reciprocal in nature. The nearby residents who breathe smoke spewn by a factory must share with the management of the factory the responsibility for the resulting social cost. True, if the factory were closed up the social cost would disappear. But the same holds for its neighbors—were they to move away no one would suffer smoke nuisance. Put another way, just as the smoke emitted by the factory imposes at least a psychic cost on its neighbors, the latter's insistence on the installation of purification devices or a reduction in the pollution-producing activity imposes a cost on the factory.

This position, though at first glance very odd (the murder victim too, is then always an accessory to the crime), grows more persuasive as one considers it further. Coase does not raise the issue as a matter of distributive justice. Rather, he suggests, because of the reciprocal structure of the externality, the traditional taxes and subsidies are likely to lead to a misallocation of resources.[1] If it is socially less costly to

[1] Thus Coase starts out with

. . . the case of a confectioner, the noise and vibrations from whose machinery disturbed a doctor in his work. To avoid harming the doctor would inflict harm on [be costly to] the confectioner. The problem posed by this case was essentially whether it was worthwhile, as a remove the neighbors from the vicinity of the factory than to reduce the quantity of pollutants emitted by the plant (taking into account the location preferences of the current residents), surely the former is the course of action which is more desirable socially.

In that case, should not a tax sometimes be levied, at least in part on those who choose to live near the factory rather than upon the factory owners?[2] Otherwise might not too many persons be induced to move near the factory thus, incidentally, increasing the magnitude of the Pigouvian tax since the social damage caused by the smoke must then rise correspondingly?

A simple model shows readily that, properly stated, the prescription of the Pigouvian tradition is (at least formally) correct. An appropriately chosen tax, levied only on the factory (without payment of compensation to local residents) is precisely what is needed for optimal resource allocation under pure competition. No tax on nearby residents is required or, taken in real terms, is even compatible with optimal resource allocation. Thus the obvious and apparently common interpretation of the Coase position is simply invalid. We will see, however, that the issue Coase himself intended to raise was rather more subtle and his conclusions are not necessarily at variance with the Pigouvian prescription as I interpret it.

II. Analysis: Should the Victims of Externalities be Taxed or Compensated?

To formalize the argument we construct an elementary general equilibrium model designed to represent in most explicit form the conditions envisioned in the Coase argument, departing from it only by an assumption of universal perfect competition, including thereby the critical stipulation that costs of negotiated and voluntary control of externalities are prohibitive. In addition, we adopt the simplifying premises that there is only one scarce resource, labor, and that the externality (smoke) only affects the cost of production of neighboring laundries, rather than causing disutility for consumers. It is easy to show (see for example, fn. 5) that neither of these simplifications, nor the assumption that there are only four activities, affects the substance of the discussion. We utilize the following notation: Let

x_1, x_2, x_3, and x_4 be the outputs of the economy's four activities, I, II, III, and IV

R be the total supply of the labor resource available

x_5 be the unused quantity of labor (which is assumed to be utilized as leisure)

result of restricting the methods of production which could be used by the confectioner, to secure more doctoring at the cost of a reduced supply of confectionery products. [Section II, p. 2]

[2] If the factory owner is to be made to pay a tax equal to the damage caused, it would clearly be desirable to institute a double tax system and to make residents of the district pay an amount equal to the additional cost incurred by the factory owner (or the consumers of his products) in order to avoid the damage. [Coase, Section IX, p. 41] An even stronger statement on this subject occurs in Buchanan and Stubblebine (Section III):

> . . . full Pareto equilibrium can *never* be attained via the imposition of unilaterally imposed taxes and subsidies until all marginal externalities are eliminated. If a tax subsidy method, rather than 'trade,' is to be introduced, it should involve bi-lateral taxes (subsidies). Not only must B's behavior be modified so as to insure that he will take the costs externally imposed on A into account, but A's behavior must be modified so as to insure that he will take the costs 'internally' imposed on B into account. [italics added]

However, in a recent letter Buchanan commented:

> In my own thinking . . . I did not ever think of this sort of [double] tax at all, and it would have surely seemed bizarre to me to suggest that taxes be levied on both the factory and the laundries. What we were proposing was the Wicksellian public-goods approach. Suppose that existing property rights allow the factory to put out the smoke . . . There is a public goods problem here; the residents get together, impose a tax on *themselves* to subsidize the factory to install the smoke prevention device.

x_{ij} be the quantity of x_i consumed by individual j $(i=1, \ldots, 5)$ $(j=1, \ldots, m)$

p_1, p_2, p_3, p_4, and p_5 be the prices of the four outputs and leisure

$u_j(x_{1j}, \ldots, x_{5j})$ be the utility function of individual j, and

$c_1(x_1)$, $c_2(x_1, x_2)$, $c_3(x_3)$ and $c_4(x_4)$ be the respective total labor cost functions for our four outputs

Here x_1 is an output whose production imposes external costs on the manufacture of x_2 (say, industry II is the oft-cited laundry industry whose costs are increased by I's smoke). To permit the full range of Coase's alternatives (moving of the factory's neighbors and elimination of smoke by the factory), each of these two products is taken to have a perfect substitute. The substitute for x_1 is x_3 whose production yields no externalities, but whose cost is different (presumably higher) than that of x_1. We may think of commodity III as identical with I, but produced in a factory equipped with smoke elimination equipment. Similarly, industry IV is taken to offer the same output as II but its operations have been relocated (at a cost) in order to avoid the effects of the externalities.[3] Thus, by changing the ratio between x_2 and x_4 the model can relocate as much of the laundry output as is desired.

All prices are expressed in terms of hours of labor so that, identically,

$$p_5 = 1 \tag{1}$$

Pareto optimality then requires maximization of the utility of any arbitrarily chosen individual, say m, subject to the requirement that there be no loss in utility to any of the $m-1$ other persons, i.e., given any feasible level for these other persons' utility. Thus the problem is[4] to maximize

$$u_m(x_{1m}, \ldots, x_{5m})$$

subject to

$$u_j(x_{1j}, \ldots, x_{5j}) = k_j \text{ (constant)} \quad (j = 1, 2, \ldots, m-1)$$

$$\sum_{j=1}^{m} x_{ij} = x_i \quad (i = 1, \ldots, 5)$$

and the labor requirement (production function) constraint

$$c_1(x_1) + c_2(x_1, x_2) + c_3(x_3) + c_4(x_4) + x_5 = R$$

We immediately obtain our Lagrangian

$$\begin{aligned} L = {} & \sum_{j=1}^{m} \lambda_j[u_j(x_{1j}, \cdots, x_{5j}) - k_j] \\ & + \sum_i \nu_i(x_i - \sum_j x_{ij}) \\ & + \mu[R - c_1(x_1) - c_2(x_1, x_2) \\ & - c_3(x_3) - c_4(x_4) - x_5] \end{aligned} \tag{2}$$

where we may take $\lambda_m = 1$, $k_m = 0$.

We use the notation u_{ji} to represent $\partial u_j/\partial x_{ij}$ and c_{ik} to represent $\partial c_i/\partial x_k$ (or dc_i/dx_k, where appropriate).

Then, differentiating in turn with respect to the x_{ij} and the x_i we obtain the first-order conditions

$$\partial L/\partial x_{ij} = \lambda_j u_{ji} - \nu_i = 0 \quad (i = 1, \ldots, 5) \quad (j = 1, \ldots, m)$$

$$\partial L/\partial x_1 = -\mu(c_{11} + c_{21}) + \nu_1 = 0$$

$$\partial L/\partial x_i = -\mu c_{ii} + \nu_i = 0 \quad (i = 2, 3, 4)$$

$$\partial L/\partial x_5 = -\mu + \nu_5 = 0$$

[3] Since product III is a perfect substitute for product I and product IV is a perfect substitute for product II, the utility function for individual j can be written as $u_j(x_{1j}+x_{3j}, x_{2j}+x_{4j}, x_{5j})$. This is, of course, a special case of the more general utility function utilized in the text, and as the reader can verify, the conclusions are totally unaffected by the use of the particular form of the utility function just described.

[4] For a more sophisticated variant of this model, using the techniques of non linear programming, see Robert Meyer.

Now, from consumer equilibrium analysis, we know that for any two commodities, a and b, and any two prices, p_a and p_b, we have $p_a/p_b = u_{ja}/u_{jb}$ $(j=1, \cdots, m)$ or $\omega_j p_i = u_{ji}$ for all i and some ω_j.

Hence, $\lambda_j u_{ji} = \lambda_j \omega_j p_i$, so that writing $s_j = \lambda_j \omega_j$ the first of our first-order conditions becomes $\nu_i = s_j p_i$ for all individuals, j. Consequently the value of s_j must equal the same number, $s = \nu_i / p_i$ for every individual, and that first equation of the first-order conditions now becomes simply $\nu_i = s p_i$ for all i. Substituting this expression for ν_i into the other first-order conditions, we obtain

$$sp_1 = \mu(c_{11} + c_{21})$$

$$sp_i = \mu c_{ii} \qquad (i = 2, 3, 4)$$

$$sp_5 = s = \mu \quad \text{since } p_5 = 1 \text{ [by (1)]} \tag{3}$$

By (3) we may then divide through the preceding conditions by $s=\mu$, and they therefore reduce just to[5]

$$\begin{aligned} p_1 &= c_{11} + c_{21} \\ p_2 &= c_{22} \\ p_3 &= c_{33} \\ p_4 &= c_{44} \\ p_5 &= 1 \end{aligned} \tag{4}$$

In other words, the optimal price for the externality-generating product is equal to the (Pareto optimal) level of its entire social[6] marginal cost, $c_{11}+c_{21}$, while the optimal price for any item, i, which generates no externalities is simply its marginal private cost, c_{ii}. To obtain these prices in our world of pure competition, one need merely levy an excise tax on item I equal to c_{21} (labor hours) dollars per unit, just as the Pigouvian tradition requires. Assuming the appropriate concavity-convexity conditions hold, this will automatically satisfy the necessary and sufficient conditions for the Pareto optimal output levels.[7] In the competitive case, where negotiation is impractical, that is all there is to the matter. The generalization to the case of n outputs, each of them imposing externalities on a number of the others, is immediate.

It is important to observe that, *the solution calls for neither taxes upon x_2, the neighboring laundry output, nor compensation to that industry* for the damage it suffers.

One way to look at the reason is that our model (and the pollution model in general) refers to the important case of *public* externalities. The laundry whose output is

[5] The analysis can also take account of constraints on the availability of land at the relevant locations, which give rise to rents that equalize costs at all locations actually utilized. If S_a and S_b represent the availability of land near and away from the factory, respectively, presumably we would add to the labor constraint in the model the two additional land-use constraints $g_a(x_1, x_2, x_3$ $+s_a = S_a$ and $g_b(x_4) + s_b = S_b$, with the quantities of unused land, s_a and s_b perhaps entering the utility functions. It then follows, just as before, that the equilibrium conditions are now $p_1 = c_{11} + c_{21} + p_a g_{a1}$; $p_2 = c_{22} + p_a g_{a2}$; $p_3 = c_{33} + p_a g_{a3}$; $p_4 = c_{44} + p_b g_{b4}$; $p_5 = 1$; $p_a = \rho_a/\mu$; $p_b = \rho_b/\mu$; where ρ_a and ρ_b are the Lagrange multipliers for the new constraints and p_a and p_b are the (labor) prices of land at the two locations. Our previous conclusions are, thus, totally unaffected. Only the smoke producer's product sells for more than its marginal private cost of labor plus land.

[6] The social cost is not c_{21} alone but is the sum of the private and the external costs together (see the illuminating terminological discussion by D. W. Pearce and Stanley Sturmey). Note that the tax, implicitly, is a tax on *smoke* not a tax on x_1, the output of the smoke producing industry. For if s is the quantity of smoke and t the unit tax we may write $t \quad c_{21} = (\partial c_2/\partial s)(ds/dx_1)$ and obviously the firm can reduce its tax rate by decreasing the second of these terms, the smokiness of its product. This point has been emphasized by Charles Plott, who showed that a fixed tax per unit of x_1 might even conceivably increase s, if s were an inferior input.

[7] Moreover, measured in real terms this is the only tax arrangement that satisfies the optimality requirements, neglecting the possibility of a lump sum tax or subsidy which does not affect the marginal conditions. F. Trenery Dolbear has shown that it is generally not possible to find an optimal tax rate that compensates fully those who suffer the effects of the externality. Since no compensation is paid to industry II, the solution that is derived here does not run into Dolbear's problem. We also do not run into the problem of a multiplicity of solutions corresponding to the various points on Dolbear's contract curve because we are dealing with a world of pure competition with a given initial distribution.

damaged by smoky air does not, by an increase in its own output, make the air cleaner or dirtier for others. As with all public goods, an increase in one user's consumption does not reduce the available supply to others.[8] Hence, the appropriate price (compensation) to a user of a public good (victim of a public externality) is *zero* except, of course, for lump sum payments. Thus, perhaps, rather than saying there is no price that will yield an optimal quantity of a public good (externality), it may be more illuminating to say that a double price is required: a nonzero price (tax) to the supplier of the good, and a zero price to the consumer. Of course, no ordinary price can do this job, but a Pigouvian tax, without compensation to those affected by an externality, can indeed do the trick.

III. What Prevents an Excessive Influx of Neighbors?

When only smoke emission is taxed, with the tax level based on the magnitude of x_2, nearby laundry output, what will prevent too many laundries from moving near the smoky factory? The answer is that, when the tax on the externality producer is set properly, the externalities themselves keep down the size of the nearby population. Moreover, the level of the tax will control both the magnitude of smoke emission and thereby (indirectly), the size of the nearby population. A high tax rate will discourage smoke and hence encourage migration into the neighborhood. A low tax rate will encourage smoke and, hence, drive residents away. A tax on smoke alone is all that is needed to control the magnitudes of *both* variables. That is why, as shown by the mathematics of the preceding section, just a tax on the smoke producer is sufficient to produce an optimal allocation of resources among all the activities in our model.[9]

A diagram may help to make the point clearer. Figure 1 shows the response of our two industries' outputs to a change in the tax rate on the polluting industry, I. We see that as the tax rate varies, industry I's output response follows the curve RR'. Thus, if the tax level is t, the output of industry I will be x_{1t}. But, because of the externalities, the output of industry II, in turn, reacts to the output of I. This relationship is described by reaction curve PP'. With $x_1 = x_{1t}$ we see that $x_2 = x_{2t}$.

The tax rate on II can vary all the way from $t=0$, yielding output combination (x_{10}, x_{20}), to a prohibitive tax rate, t_p, that drives I out of business altogether, so that $x_1 = 0$ and $x_2 = x_{2p}$. Obviously, the ratio x_1/x_2 then decreases monotonically as the tax rate increases and, assuming continuity, there will be some intermediate tax rate at which the two activities will be in balance. The tax will keep x_1 in check while the external cost imposed by x_1 on industry II will keep x_2 to the right relative level. There is no need for a separate tax on II to achieve this goal.

[8] In his discussion of these matters Coase seems at one point to skate awfully close to an error analogous to the confusion between pecuniary and technological externalities. He writes (section IX):

> The tax that would be imposed would . . . increase with an increase in the number of those in the vicinity . . . But people deciding to establish themselves in the vicinity of the factory will not take into account [the resulting] fall in the value of production which results from their presence. This failure to take into account costs imposed on others is comparable to the action of a factory-owner in not taking account the harm resulting from his emission of smoke. [p. 42]

This is analogous to the argument that where the supply curve of labor is rising an increase in output by firm A must produce externalities, by raising B's labor costs. But, of course, this merely represents a transfer from B to his workers and is not a real net cost to society. For that reason, as is well known, pecuniary externalities do *not* lead to resource misallocation. Like a price change, the variation in taxes constitutes a pecuniary externality. Both have real consequences but they are merely "movements along" the production and utility functions, i.e., any given vector of inputs will be able to produce the same outputs as before the change in tax rates, and any vector of output levels will still be able to yield the same utility levels.

[9] See the Appendix for a discussion of an argument by Buchanan and Stubblebine which is related to Coase's.

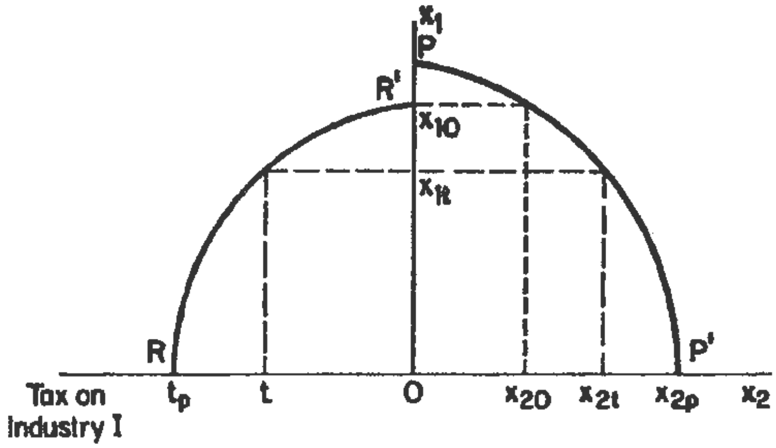


FIGURE 1

In order for this arrangement to work it is clearly necessary that the laundries *not* be compensated (at the margin) for the smoke damage they suffer. If they received in compensation an amount which varied with the magnitude of the smoke damage, that externality would not restrict the level of laundry activity near the factory. If the laundry operators' smoke costs were offset by damage compensation payments, obviously they would lose the economic incentive to eschew the vicinity of the smoky factory[10] and then Coase's tax on laundries would indeed be required to keep them away. But then the tax would be needed only to sop up the compensation payments which should never have been given in the first place.

IV. Multiple Local Maxima in the Coase Model

Coase's discussion is, however, right in pointing out the possibility that the economy may make the wrong choice between smoke elimination and laundry relocation: however the source of the problem, a multiplicity of local maxima, does not emerge clearly. Coase writes:

> Assume that a factory which emits smoke is set up in a district previously free from smoke pollution, causing damage valued at $100 per annum. Assume that the taxation solution is adopted and that the factory owner is taxed $100 per annum as long as the factory emits the smoke. Assume further that a smoke-preventing device costing $90 per annum to run is available. In these circumstances, the smoke-preventing device would be installed.
>
> . . . Yet the position achieved may not be optimal. Suppose that those who suffer the damage could avoid it by moving to other locations or by taking various precautions which would cost them, or be equivalent to a loss in income of, $40 per annum. Then there would be a gain in the value of production of $50 if the factory continued to emit its smoke and those now in the district moved elsewhere or made other adjustments to avoid the damage. [Section IX]

One curious feature of this example is its assumption that while smoke damage is $100, the cost of moving to other locations is only $40. Under these circumstances one

[10] Of course, as smoke cost increases in the neighborhood of the factory, rents will fall to some extent and serve as partial compensation to the laundries. However, this does not change the analysis fundamentally. It is analogous to the case of rise in the price of an input which, as is well known, will tend to reduce the output of competitive firms, even though prices of other complementary inputs fall as a result. As the discussion of footnote 5 shows, explicit consideration of the price of land does not change the character of the solution.

may well wonder why people living near the factory do not just move elsewhere on their own initiative. Moreover, this may not simply be a matter of the numbers he happens to have chosen. The problem arises whenever the cost of moving away from the factory is less than the cost of elimination of the smoke, which in turn is less than the cost of the smoke damage, as the logic of Coase's example requires.

It is perhaps more important to recognize that the example presents us with a choice between (at least) two local optima. As will be argued later, a multiplicity of maxima is generally rendered more likely by the presence of externalities so that this issue is not a pecularity of Coase's illustrations. The first of the two local optima in Coase's example (call it solution A) involves zero smoke emission and a full complement of residents near the factory. In the second optimum (solution B) no one remains in residence next to the factory and there is no restriction in smoke emission by the plant. Assuming that the (undesirable) initial position is the only other possibility, as Coase seems to suggest, which of these two will in fact be the global optimum depends on the cost of moving everyone away (m dollars) and the cost of elimination of the smoke (s dollars).

Assume with Coase that the initial cost of smoke damage is \$100, that $s<100$, but that $s<m$ so that it is cheaper to eliminate the smoke than to move the factory's neighbors. In this case, A is obviously the optimal solution. Since inhabitants surround the plant, and smoke emission, by assumption, cannot be changed by small amounts, the incremental social damage of an increase in smoke emission is \$100. Thus the correct Pigouvian tax is \$100 and, since $s<100$, with such a tax it will pay the factory to do the right thing by society—to install the smoke eliminator.

Now assume instead that $m<s<100$ (it is cheaper to move people than to stop the smoke). This time B is the optimal solution, and since under B no one lives near the factory, the incremental cost of smoke is clearly zero. Therefore the proper Pigouvian tax is zero, a value that induces the factory to continue smoking, and its neighbors will find it advantageous (since $100>m$) to exit (coughing) from the area. Thus the zero Pigouvian tax value automatically satisfies the requirements of solution B when B is optimal just as the \$100 Pigouvian tax leads to solution A when A is optimal.

Of course, if B happens to be the true global optimum and society mistakenly imposes the \$100 Pigouvian tax appropriate for (local) optimum A, the economy may well end up with the inferior equilibrium A. This is the usual difficulty one encounters whenever there is a multiplicity of maxima, a problem that Pigou so clearly recognized (pp. 140, 224).

V. Departures from the Optimum and Adjustments in the Tax

If there is a departure from the optimal solution, for whatever reason, the value of the Pigouvian tax need not change. If, for example, B is the global optimum so that the optimal tax is zero, that tax need not be increased if a few (misguided) individuals choose to move back near the factory so that additional smoke now incurs (say) \$50 in damage. *At the optimal solution* the marginal cost of smoke is zero, and the equilibrium Pigouvian tax remains zero—it does not increase to \$50.

Here we have arrived at the issue which, I now understand, was really Coase's main point in the portion of his article we are considering. He writes in a letter:

> . . . Let us assume your optimum tax is imposed. Now suppose that A establishes himself near the plant which produces the damaging emissions and thus

increases the amount of damage. Would your tax increase? My guess is that it would not (certainly if your tax system is right it should not). The tax system I was attacking was one which would in these circumstances, automatically lead to an increase in the tax as the damage increased.

This point is, surely, quite different from the issue he is usually interpreted to have raised (see the quotations in fn. 1, above, which suggest how the "usual interpretation" arose). It is, however, not inconsistent with the optimal solution derived in the previous section nor is it inconsistent with what I take to be the Pigouvian tradition.

But even on this issue Coase's strictures are not necessarily valid. Suppose that a regulator, having no way of calculating the *optimal* values of the Pigouvian tax is, however, able to determine the value of any marginal social damage at any point in time. *Faut de mieux* he therefore sets a tax rate equal to *current* marginal social damage on the smoke producer. This causes him to reduce his smoke, and so brings more laundries into the neighborhood. The tax is then readjusted to equal the new (higher) value of damage per puff of smoke, more laundries move in, and so on. Will this process of trial and error adjustments of the tax level, always setting it equal to current marginal smoke damage, converge to the optimum of Section II? That is, will the sequence of tax values converge to the optimal Pigouvian tax level, and will resource allocation approach optimality? That now seems to be Coase's main question.

Obviously, such a learning process always involves wastes and irreversabilities, just like the process of convergence of competitive prices to their equilibrium values in the absence of externalities. But if we follow the usual practice of assuming away these costs, one can show that the process may be expected to converge to the optimum, provided the equilibrium is unique and stable. That is, there is then nothing inherently different about gradually moving taxes and prices towards their equilibrium here, and the process of adjustment toward competitive equilibrium when there are no externalities.

Specifically, letting s_t represent the tax per unit on commodity 1 at time t, and G_i be the ith adjustment function we may set

$$\begin{aligned} &dx_{1t}/dt = G_1[p_{1t} - s_t - c_{11}(x_{1t})] \\ (5)\quad &dx_{2t}/dt = G_2[p_{2t} - c_{22}(x_{1t}, x_{2t})] \\ &dx_{it}/dt = G_i[p_{it} - c_{ii}(x_{it})] \qquad (i = 3, 4) \end{aligned}$$

$$(6)\ s_t = c_{21}(x_{1t}, x_{2t}) \qquad p_{it} = f_i(x_{1t}, \ldots, x_{5t})$$

and where, as usual, we take

$$(7)\qquad G_i(0) = 0$$

$$(8)\qquad G_i' > 0$$

Going back to Section II, when optimality conditions (4) hold, we see by substituting them into (5) that all $dx_{it}/dt = 0$, i.e., (4) is indeed an equilibrium position for the dynamic system (5)–(8). Furthermore, any solution that does not satisfy (4) must involve at least one nonzero argument in the adjustment functions (5), and so no solution that fails to satisfy (4) can be an equilibrium.

It follows that if the dynamic system (5)–(8) is stable, and the solution to (4) is unique, the process with taxes set equal to *current* marginal damage and imposed *only on the polluter* will converge toward the optimum. One does not need to have calculated the optimal tax values from the beginning and stick to them.

The reason this process of simultaneous learning and adjustment does not work in Coase's example is that it involves (at least) two local maxima, as we have already noted. And in such a case, obviously, the adjustment mechanism may well take us to the wrong maximum. Unfortunately, as we will see presently, in the presence of externalities, a multiplicity of maxima is all too likely to be with us.

VI. Implementation Problems

Despite the validity in principle of the tax-subsidy approach of the Pigouvian tradition, in practice it suffers from serious difficulties. For we do not know how to estimate the magnitudes of the social costs, the data needed to implement the Pigouvian tax-subsidy proposals. For example, a very substantial portion of the cost of pollution is psychic; and even if we knew how to evaluate the psychic cost to some one individual we seem to have little hope of dealing with effects so widely diffused through the population.[11]

This would not necessarily be very serious if one could hope to learn by experience. One might try any plausible set of taxes and subsidies and then attempt, by a set of trial and error steps, to approach the desired magnitudes. Unfortunately, convergence toward the desired solution by an iterative procedure of this sort requires some sort of measure of the improvement (if any) that has been achieved at each step so that the next trial step can be adjusted accordingly. But we do not know the socially optimal composition of outputs, so we simply have no way of judging whether a given change in the trial tax values will even have moved matters in the right direction.

These difficulties are compounded by another characteristic of externalities which has already been mentioned—the likelihood that in the presence of externalities there will be a multiplicity of local maxima (see Richard Portes, D. A. Starrett, and Baumol). Consequently, even if an iterative process were possible it might only drive us toward a local maximum, and may thus fail to take advantage of the really significant opportunities to improve economic welfare.

A simple model in the spirit of that of Section II can be used to show that the presence of "strong" externalities can be expected to produce a violation of the convexity conditions in whose absence one normally finds a multiplicity of local optima.

Let us assume (to permit the use of a two-dimensional diagram) that there exist only the first two of our four activities (the smoky output, x_1, and nearby laundry, x_2), and that their respective cost functions are, as before, $c_1(x_1)$ and $c_2(x_1, x_2)$. As a result, the equation of the production possibility locus is

$$c_1(x_1) + c_2(x_1, x_2) = R$$

For convenience let us use k as a parameter measuring the strength of the (marginal) externality.[12] Assume first that there are diminishing returns (increasing costs) in the production of the two outputs, and that there are no marginal external effects so that $k=0$. (At the margin industry I's output produces no smoke or smoke is harmless to industry II.) In that case it is easy to show that the production possibility locus must satisfy $dx_2^2/dx_1^2 < 0$, i.e., that the locus must assume the general shape AC_0B in Figure 2 with the concavity property required by the second-order conditions.

Now, suppose that the activity of in-

[11] For an excellent discussion of some of the work done in trying to implement Pigouvian taxes in practice, see Allen Kneese and Blair Bower, esp. ch. 6 and 8. The difficulty of determining the magnitude of the Pigouvian tax-subsidy level is one of Coase's major points, one that seems often to be overlooked in discussions of his paper. Thus Coase writes in a letter, "The view I expressed in my article was not that such an optimum tax system (levied solely on the damage producing firm) was inconceivable but that I could not see how the data on which it would have to be based could be assembled." An interesting approach to application for the small numbers case that is based on the decomposition principle of mathematical programming is presented by Davis and Whinston (1966).

[12] E.g., k may be interpreted as $\partial^2 c_2/\partial x_1 \partial x_2$, i.e., the additional marginal resources cost of output 2 resulting from a unit increase in output 1.

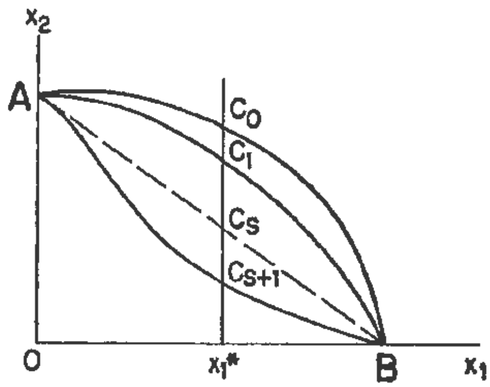


FIGURE 2

dustry I does produce some external damage ($k>0$). What happens to the production possibility locus? First I will argue that neither of its end points, A or B, will normally be affected. At point B, laundry output, x_2, is zero. Hence, no matter how much smoke is produced, there is no laundry output to be damaged. Point B is therefore invariant with the magnitude of k. Similarly, at A, the smoke creating output is zero. Consequently, no matter how smoky the process of producing output II may be (no matter how large the value of k) the total smoke emitted will be (output x_1) · (smoke per unit of output) $=0$, since the first of these factors is zero. Thus the position of point A remains invariant with the magnitude of k.

The effect on intermediate points such as C_0 on the locus is quite different. As k increases it takes increasing quantities of resources to produce a given volume of laundry. Thus, with any fixed value of x_1, say x_1^*, as k increases, the quantity of laundry that can be turned out with a given quantity of resources, R, must decline. Point C_0 will be pushed down to some lower point, C_1. With a still greater value of k it will be lowered still further. As smoke damage increases without limit it will take larger and larger quantities of resources to turn out a given quantity of laundry and eventually we approach a limit point γ on the horizontal axis, at which it is no longer possible to produce clean clothes with any finite quantity of resources.

Now draw in straight line segment AB whose position does not vary with k since neither A nor B does. It is clear that as k increases we will eventually come to some point C_s beyond which all remaining points in the sequence C_{s+1}, C_{s+2}, . . . lie below AB. Beyond this point, obviously, the second-order conditions must be violated, as the production possibility curve approaches the axes, AOB.

Thus we see that the presence of sufficiently strong detrimental externalities will generally produce a violation of the second-order conditions. Only in the presence of insignificant externalities can one have any degree of confidence that the convexity conditions will hold.[13]

It is easy to offer an intuitive reason indicating how the presence of externalities increases the likelihood of a multiplicity of maxima, a reason that suggests that the problem is very real and potentially very serious in practice. Where a particular activity reduces the efficiency of another it becomes plausible that the optimal level of that activity, at least at some particular locations, is zero. If there are one hundred possible locations for the plants of a smoke-producing industry the worst possible solution might be to place some plants in each candidate location. *Any* solution leaving at least some combination of smoke-free areas may be preferable, and may well constitute a local maximum.

To make the point more concretely, suppose we are dealing with an island separated by a ridge of mountains that pre-

[13] The analysis can be extended to the case of n activities and externalities that enter utility as well as production functions. The analysis here confines itself to externalities producing inefficiencies on the production side following a suggestion of Jacob Marschak that the argument is more persuasive if framed in these terms.

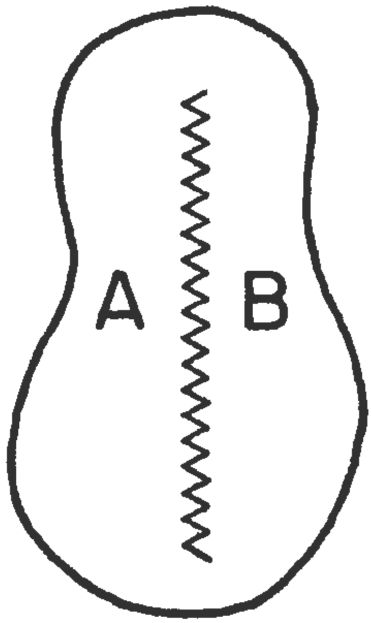


FIGURE 3

vent smoke from going from one side to the other (Figure 3). Let S_a and S_b be the volume of smoke-producing activity located on the two respective sides of the island, and let P_a and P_b be the corresponding number of residents living there. Let $S_a+S_b=S$ and $P_a+P_b=P$. Then, if the social cost of the smoke is great enough, there will obviously be at least two local optima: ($P_a=P$, $P_b=0$, $S_a=0$, $S_b=S$) and ($P_a=0$, $P_b=P$, $S_a=S$, $S_b=0$). For either of these arrangements keeps the smoke and the people apart. This does not mean, of course, that the two solutions are equally desirable. If *A* offers great scenic attractions while *B* is closer to raw materials we may expect the former of the two local maxima to be preferable. We cannot preclude the possibility of a third (interior) maximum, for once there is some industrial activity on each of the two sides of the island there may be some least cost distribution of people and industrial activity. But we see that we may well expect to encounter *at least* two local maxima. With more separated locations and more sources of externalities the number of combinations of zero-valued variables that constitute local maxima may well grow astronomically.

The presence of a number of local maxima clearly means that an "improvement" may merely represent a move toward some minor peak in the social welfare function and it can, therefore, impose serious opportunity losses on society. All in all, we are left with little reason for confidence in the applicability of the Pigouvian approach, literally interpreted. We do not know how to calculate the required taxes and subsidies and we do not know how to approximate them by trial and error.

VII. An Alternative Approach—Adjustment of Taxes to Achieve Acceptable Externality Levels

There is an alternative approach to the matter that seems perfectly natural. On issues as important as those we are discussing, given the limited information at our disposal, it is perfectly reasonable to act on the basis of a set of minimum standards of acceptability. If, say, we treat the sulphur content of the atmosphere as one of the outputs of the economic system, it is not unreasonable to select some maximal level of this pollutant that is considered satisfactory and to seek to determine a tax on the offending inputs or outputs capable of achieving the chosen standard. This is precisely the approach employed in the formulation of stabilization policy, where it is decided that an employment rate exceeding w percent and a rate of inflation exceeding ν percent per year are simply unacceptable, and fiscal and monetary measures are then designed accordingly.[14]

[14] As this discussion indicates, I join Wellicz in refusing to abandon externalities policy entirely to Little's "administrative decisions" (p. 184) or to Ralph Turvey's "applied economist" (p. 313). For further discus-

The advantages (as well as the limitations) of this approach are clear—unlike the Pigouvian procedure, it promises to be operational because it requires far less information for its implementation. Moreover, it utilizes global measures and avoids direct controls with all of their heavy administrative costs and their distortions of consumer choice and inefficiencies. It does not use the police and the courts as the prime instrument to achieve the desired modification of the outputs of the economy. Its effects are long lasting, not depending on the vigor of an enforcement agency, which all too often proves to be highly transitory. Unlike most other measures that have been proposed in the area it need not add to the mounting financial burdens of the state and local governments. Finally, it can be shown that, unlike any system of direct controls, it promises, at least in principle, to achieve decreases in pollution or other types of damage to the environment at minimum cost to society.[15]

One can expect an acceptability criterion procedure to be operational because policy makers think quite naturally in terms of minimum acceptability standards, and while it is no doubt an exaggeration to say that they can arrive at them easily, there are all sorts of precedents indicating that such standards can be decided upon in practice.

Though we are unlikely to be able to determine in advance precisely a set of tax values that will achieve the desired output standards, the output level achieved by a given tax arrangement is readily observed and, at least in principle, it is possible to learn by trial and error, continuing the direction of change of any tax modifications that turn out to bring outputs closer to their target levels. Since the procedure is a satisficing rather than a maximizing approach the possibility of a multiplicity of maxima is not relevant.

That is to say, one generally expects a considerable number of solutions to satisfy a particular set of acceptability conditions (various resource allocation patterns may be able to achieve a given set of reductions in pollution levels) *whether or not the second-order conditions are satisfied.* If several of these do so, then the essence of the satisficing approach is that one simply utilizes the first of the acceptable solutions that is discovered. One gives up any attempt to achieve any standard of optimality (other than minimization of cost[16] for a given degree of protection of the environment) and rests content with *any* solution that happens to satisfy the standards that have been selected.

sion see Baumol and Wallace Oates. For an earlier proposal that is very similar in spirit, see John H. Dales, ch. 6.

[15] This proposition has been suggested elsewhere (see, for example, Kneese and Bower, chs. 5 and 7; Larry Ruff, p. 79), and will be fairly obvious to anyone familiar with the analysis of the allocative effects of price changes and their efficiency properties. Specifically, suppose it is desired to reduce the pollution content of a river by k percent. Obviously a k percent reduction in the number of gallons emitted by each of the plants discharging wastes into the river will generally not be the desired solution. The theorem in question then asserts the following:

Given the production of any desired vector of final outputs by the plants along the river, a tax per gallon of effluent sufficient to reduce the overall pollution content of the river to the desired level will automatically achieve this decrease at minimum total cost to all plants combined.

The proof of the theorem is a straightforward exercise in constrained maximization (see Baumol and Oates). It works, of course, because the lower the marginal cost of reduction in pollution outflows of a particular plant, the larger the reductions it will pay it to undertake to avoid the corresponding tax payment.

What is surprising about the proposition, if anything, is that, unlike many results in welfare analysis, it does not require the firms along the river, or any other firms, to be perfect competitors, nor does it have to assume that they maximize profits rather than share of market or growth or some other target variable. All it requires is that the firms wish to produce whatever output they select at minimum cost to themselves.

[16] Of course it is conceivable that there may be more than one local *cost* minimum. In that case an effluent charge that yields an acceptable pollution level may not yield the global cost minimum. This may be something that practical policy simply has no way of avoiding.

Thus, the acceptability criterion approach does not dispose of the difficulties involved in finding a true optimum—rather it sweeps those difficulties under the rug. Even with pollution reduced to acceptable levels, there will remain the possibility that the (undiscovered) global optimum offers us a world far better than what we have managed to achieve—if only we knew how to attain it. But if we permit ourselves to be paralyzed by councils of perfection we may have still greater cause for regret.

It may be that with time we can learn to improve the workings of a set of standards of acceptability. If, say, it turns out to be unexpectedly cheap to attain the initial pollution standards, it may be reasonable to tighten the standards on the presumption that marginal costs will not yet have equalled the marginal social benefits. Successive modifications in the criteria based on experience and revaluation may produce results that on the whole are not too bad.

If firms are put on notice that the acceptability standards may well be modified in the future this may lead them to construct what George Stigler describes as more flexible plants,—plants which are designed to keep down the cost of response to changes in standards. Of course, flexibility itself is not costless. However, it may be precisely what is appropriate for a society which is only beginning to learn how to grapple with its environmental problems.

Appendix

Buchanan, Stubblebine and Taxation of Both Parties to an Externality

Buchanan and Stubblebine have raised objections to the Pigouvian solution similar to those offered by Coase (see fn. 2, above). Much of their discussion deals with the case where voluntary negotiation in the presence of externalities will lead automatically to a Pareto optimum. As already admitted, in this case a Pigouvian tax will only cause trouble. However, the authors also appear to offer an argument against the Pigouvian tax for the case in which negotiation is absent.

Their argument, if I understand it correctly, is that after industry I adjusts to a Pigouvian tax on its output, for that industry the marginal yield of an increase in x_1 is zero. However, for industry II, at the point γ the marginal yield of x_1 is $c_{21}<0$. There must, consequently, be potential gains from trade between the two industries. They state:

> So long as $[(\partial c_2/\partial x_1)/(\partial c_2/\partial x_2)]$ remains nonzero, a Pareto-relevant marginal externality remains, despite the fact that the full 'Pigouvian solution' is attained. The apparent paradox here is not difficult to explain. Since, as postulated, [II] is not incurring any cost in securing the change in [I's] behavior, and since there remains, by hypothesis, a marginal diseconomy, further 'trade' can be worked out between the two parties. . . . The important implication to be drawn is that full Pareto equilibrium can never be attained via the imposition of unilaterally imposed taxes and subsidies . . .
> [Section III, pp. 382–83]

No doubt this is true—in a competitive situation two interrelated industries can generally increase their joint profits ("gain from trade") by collusion at the expense of the general public. In the case under discussion, if the output of x_1 is reduced it is true that industry I will lose nothing and industry II will gain c_{21}. However, society as a whole will experience no net gain.

Since the analysis deals exclusively with resource *allocation* we must assume that the labor released by the reduced value of x_1 will be employed elsewhere to produce more of some other output or more leisure. Consequently, the goods or services represented by the t units in taxes must be redistributed to the general public either by remission of another tax, increased provision of government services or some other means.

We may now evaluate the consequences of a unit increase in the output of x_1 on the entire society by summing up the direct effects on each of the three groups immediately

	Industry I	Industry II	Consumers	General Public
Incremental gain or revenue	p		$u_1 = c_{11} + t$	$t = c_{21}$
Incremental cost	$(c_{11}+t) = (c_{11}+c_{21})$	c_{21}	p	

concerned: industry I, industry II, consumers, and the consequences of the tax receipts for the general public (which encompasses all consumers and producers, including those already mentioned). These are shown in the table above Adding up the incremental gains and revenues we see that the net social gain is zero, precisely as optimality requires. There is only a redistribution from industry II to the general public.

In a recent letter Buchanan comments:

> As for the nonoptimality of a unilaterally imposed tax, the problem here is that income effects enter to make the benefit-receiving side change behavior so that still further adjustments would be necessary . . . Our point was that this new position would not be one of full equilibrium if income effects enter. The laundries would now find that they secure the benefits of cleaner air without cost to themselves. Presumably this would make them do more laundry. This change in behavior would in turn change the apparent optimal solution. Admittedly, the imposed solution qualifies as Pareto-optimal if further trading is prohibited. And here Pareto-equilibrium does take on a different meaning from Pareto-optimal. Gains-from-trade exist, as you agree and, once these take place, we are not in an optimal solution.

In this paper I deal with the case where trading fails to take place not because it is prohibited, but because (as seems characteristic of our most important externalities problems in reality) large numbers make trading virtually impossible to arrange (where have we seen automobile drivers pay one another to cut down their exhaust?). Moreover, one must distinguish between the role of Buchanan's income effect and that of "further trading." Of course, further trading can destroy the optimality of the results achieved by a Pigouvian tax. For, as just argued, in that case the two affected groups gain by exploiting the community. On the other hand, the "income effect"—the influx of laundries near the factory as clean air becomes cheaper is precisely the reason a tax on the smoke producer alone can lead *everyone* to behave Pareto optimally (see Section III).

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This is Exhibit B
referred to in the Affidavit
of JUNE PARKER
sworn before me this 17th day
of DECEMBER 2018

A Commissioner for taking Affidavits
within British Columbia

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Environmental Economics: A Survey

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I. *Introduction*

WHEN THE ENVIRONMENTAL revolution arrived in the late 1960s, the economics profession was ready and waiting. Economists had what they saw as a coherent and compelling view of the nature of pollution with a straightforward set of policy implications. The problem of externalities and the associated market failure had long been a part of microeconomic theory and was embedded in a number of standard texts. Economists saw pollution as the consequence of an absence of prices for certain scarce environmental resources (such as clean air and water), and they prescribed the introduction of surrogate prices in the form of unit taxes or "effluent fees" to provide the needed signals to economize on the use of these resources. While much of the analysis was of a fairly general character, there was at least some careful research underway exploring the application of economic solutions to certain pressing environmental problems (e.g., Allen Kneese and Blair Bower 1968).

The economist's view had—to the dismay of the profession—little impact on the initial surge of legislation for the control of pollution. In fact, the cornerstones of federal environmental policy in the United States, the Amendments to the Clean Air Act in 1970 and to the Clean Water Act in 1972, *explicitly* prohibited the weighing of benefits against costs in the setting of environmental standards. The former directed the Environmental Protection Agency to set maximum limitations on pollutant concentrations in the atmosphere "to protect the public health"; the latter set as an objective the "elimination of the discharge of *all* [our emphasis] pollutants into the navigable waters by 1985."[1]

The evolution of environmental policy, both in the U.S. and elsewhere, has inevitably brought economic issues to the fore; environmental regulation has necessarily involved costs—and the question of how far and how fast to push for pollution control in light of these costs has entered into the public debate. Under Executive Order 12291 issued in 1981, many proposed environmental measures have been subjected to a benefit-cost test. In addition, some more recent pieces of environmental legislation, notably the Toxic Substances Control Act (TSCA) and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), call for weighing benefits against costs in the setting of standards. At the same time, economic incentives for the containment of waste discharges have crept into selected regulatory measures. In the United States, for example, the 1977 Amendments to the Clean Air Act introduced a provision for "emission offsets" that has evolved into the Emissions Trading Program under which sources are allowed to trade "rights" to emit air pollutants. And outside the United States, there have been some interesting uses of effluent fees for pollution control.

This is a most exciting time—and perhaps a critical juncture—in the evolution of economic incentives for environmental protection. The Bush Administration proposed, and the Congress has introduced, a measure for the trading of sulfur emissions for the control of acid rain under the new 1990 Amendments to the Clean Air Act. More broadly, an innovative report from within the U.S. Congress sponsored by Senators Timothy Wirth and John Heinz, *Project 88: Harnessing Market Forces to Protect Our Environment* (Robert Stavins 1988) explores a lengthy list of potential applications of economic incentives for environmental management. Likewise, there is widespread, ongoing discussion in Europe of the role of economic measures for pollution control. Most recently in January of 1991, the Council of the Organization for Economic Cooperation and Development (OECD) has gone on record urging member countries to "make a greater and more consistent use of economic instruments" for environmental management. Of particular note is the emerging international concern with global environmental issues, especially with planetary warming; the enormous challenge and awesome costs of policies to address this issue have focused interest on proposals for "Green Taxes" and systems of tradable permits to contain global emissions of greenhouse gases. In short, this seems to be a time when there is a real opportunity for environmental economists to make some valuable contributions in the policy arena—if, as we shall argue, they are willing to move from "purist" solutions to a realistic consideration of the design and implementation of policy measures.

Our survey of environmental economics is structured with an eye toward its policy potential. The theoretical foundations for the field are found in the theory of externalities. And so we begin in Section II with a review of the theory of environmental regulation in which we explore recent theoretical results regarding the choice among the key policy instruments for the control of externalities: effluent fees, subsidies, and marketable emission permits. Section III takes us

[1] Although standards were to be set solely on the basis of health criteria, the 1970 Amendments to the Clean Air Act did include economic feasibility among its guidelines for setting source-specific standards. Roger Noll has suggested that the later 1977 Amendments were, in fact, more "anti-economic" than any that went before. See Matthew McCubbins, Roger Noll, and Barry Weingast (1989) for a careful analysis of this legislation.

from the theory of externalities to policy applications with a focus on the structuring and implementation of realistic measures for environmental management. This section reviews the work of environmental economists in trying to move from formal theorems to measures that address the variety of issues confronting an environmental regulator. We describe and evaluate briefly, as part of this treatment, the U.S. and European experiences with economic incentives for pollution control. In addition, we explore a series of regulatory issues—centralization versus decentralization of regulatory authority, international effects of domestic environmental policies, and enforcement—matters on which environmental economists have had something to say.

In Section IV, we turn to the measurement of the benefits and costs of environmental programs. This has been a particularly troublesome area for at least two reasons. First, many of the benefits and costs of these programs involve elements for which we do not have ready market measures: health benefits and aesthetic improvements. Second, policy makers, perhaps understandably, have proved reluctant to employ monetary measures of such things as "the value of human life" in the calculus of environmental policy. Environmental economists have, however, made some important strides in the valuation of "nonmarket" environmental services and have shown themselves able to introduce discussion of these measures in more effective ways in the policy arena.

In a survey in this *Journal* some fifteen years ago, Anthony Fisher and Frederick Peterson (1976) justifiably contended that techniques for measuring the benefits of pollution control are "to be taken with a grain of salt" (p. 24). There has been considerable progress on two distinct fronts since this earlier survey. First, environmental (and other) economists have shown considerable ingenuity in the development of techniques – known as indirect market methods—that exploit the relationships between environmental quality and various marketed goods. These methods allow us to infer the value of improved environmental amenities from the prices of the market goods to which they are, in various ways, related. Second, environmental economists have turned to an approach regarded historically with suspicion in our profession: the direct questioning of individuals about their valuation of environmental goods. Developing with considerable sophistication the so-called "contingent valuation" approach, they have been able to elicit apparently reliable answers to questions involving the valuation of an improved environment. In Section IV, we explore these various methods for the valuation of the benefits and costs of environmental programs and present some empirical findings.

In Section V, we try to pull together our treatment of measuring benefits and costs with a review of cases where benefit-cost analyses have actually been used in the setting of environmental standards. This provides an opportunity for an overall assessment of this experience and also for some thoughts on where such analyses are most needed. We conclude our survey in Section VI with some reflections on the state of environmental economics and its potential contribution to the formulation of public policy.

Before turning to substantive matters, we need to explain briefly how we have defined the boundaries for this survey. For this purpose, we have tried to distinguish between "environmental economics" and "natural resource economics." The distinguishing characteristic of the latter field is its concern with the intertemporal allocation of renewable and nonrenewable resources. With its origins in the seminal paper by Harold Hotelling

(1931), the theory of natural resource economics typically applies dynamic control methods of analysis to problems of intertemporal resource usage. This has led to a vast literature on such topics as the management of fisheries, forests, minerals, energy resources, the extinction of species, and the irreversibility of development over time. This body of work is excluded from our survey. The precise dividing line between environmental economics and natural resource economics is admittedly a little fuzzy, but in order to keep our task a manageable one, we have restricted our survey to what we see as the two major issues in environmental economics: the regulation of polluting activities and the valuation of environmental amenities.

II. *The Normative Theory of Environmental Regulation*

The source of the basic economic principles of environmental policy is to be found in the theory of externalities. The literature on this subject is enormous; it encompasses hundreds of books and papers. An attempt to provide a comprehensive and detailed description of the literature on externalities theory reaches beyond the scope of this survey. Instead, we shall attempt in this section to sketch an outline of what we see as the central results from this literature, with an emphasis on their implications for the design of environmental policy. We shall not address a number of formal matters (e.g., problems of existence) that, although important in their own right, have little to say about the structure of policy measures for protection of the environment.

A. *The Basic Theory of Environmental Policy*[2]

The standard approach in the environmental economics literature characterizes pollution as a public "bad" that results from "waste discharges" associated with the production of private goods. The basic relationships can be expressed in abbreviated form as:

$$U = U(X,Q) \quad (1)$$
$$X = X(L,E,Q) \quad (2)$$
$$Q = Q(E) \quad (3)$$

where the assumed signs of the partial derivatives are $U_X > 0$, $U_Q < 0$, $X_L > 0$, $X_E > 0$, $X_Q < 0$, and $Q_E > 0$. The utility of a representative consumer in equation (1) depends upon a vector of goods consumed (X) and upon the level of pollution (Q). Pollution results from waste emissions (E) in the production of X, as indicated in (2). Note that the production function in (2) is taken to include as inputs a vector of conventional inputs (L), like labor and capital, the quantity of waste discharges (E), and the level of pollution (Q). In this formulation, waste emissions are treated simply as another factor of production; this seems reasonable since attempts, for example, to cut back on waste discharges will involve the diversion of other inputs to abatement activities—thereby reducing the availability of these other inputs for the production of goods. Reductions in E, in short, result in reduced output. Moreover, given the reasonable assumption of rising marginal abatement costs, it makes sense to assume the usual curvature properties so that we can legitimately draw isoquants in L and E space and treat them in the usual way.

[2] For comprehensive and rigorous treatments of the general ideas presented in this section, see, for example, William Baumol (1972), Baumol and Wallace Oates (1988), Paul Burrows (1979), and Richard Cornes and Todd Sandler (1986). We have not included in this survey a literature on conservation and development that has considered issues of irreversibility in the time of development for which the seminal papers are John Krutilla (1967), and Kenneth Arrow and Anthony Fisher (1974). This literature is treated in the Anthony Fisher and Peterson survey (1976) and, more recently, in Anthony Fisher (1981, ch. 5).

The production function also includes as an argument the level of pollution (Q), since pollution may have detrimental effects on production (such as soiling the output of the proverbial laundry or reducing agricultural output) as well as producing disutility to consumers. The level of pollution is itself some function of the vector of emissions (E) of all the producing units. In the very simplest case, Q might be taken to equal the sum of the emissions over all producers.[3]

One extension of the model involves the explicit introduction of "defensive" activities on the part of "victims." We might, for example, amend the utility function:

$$U = U[X, F(L,Q)] \qquad (4)$$

to indicate that individuals can employ a vector of inputs (L) to lessen, in some sense, their exposure to pollution. The level of pollution to which the individual is actually exposed (F) would then depend upon the extent of pollution (Q) and upon the employment of inputs in defensive activities (L). We could obviously introduce such defensive activities for producers as well. We thus have a set of equations which, with appropriate subscripts, would describe the behavior of the many individual households and firms that comprise the system.

It is a straightforward exercise to maximize the utility of our representative individual (or group of individuals) subject to (2) and (3) as constraints along with a further constraint on resource availability. This exercise produces a set of first-order conditions for a Pareto-efficient outcome; of interest here is the condition taking the form:

$$\frac{\partial X}{\partial E} = -\left[\sum\left(\frac{\partial U}{\partial Q}\frac{\partial Q}{\partial E}\right) \Big/ \frac{\partial U}{\partial X} + \sum\left(\frac{\partial X}{\partial Q}\frac{\partial Q}{\partial E}\right)\right] \qquad (5)$$

Equation (5) indicates that polluting firms should extend their waste discharges to the point at which the marginal product of these emissions equals the sum of the marginal damages that they impose on consumers [the first summation in (5)] and on producers [the second summation in (5)]. Or, put slightly differently, (5) says that pollution-control measures should be pursued by each polluting agent to the point at which the marginal benefits from reduced pollution (summed over all individuals and all firms) equal marginal abatement cost.

Another of the resulting first-order conditions relates to the efficient level of defensive activities:

$$\frac{\partial U}{\partial F}\frac{\partial F}{\partial L} = \frac{\partial U}{\partial X}\frac{\partial X}{\partial L} \qquad (6)$$

which says simply that the marginal value of each input should be equated in its use in production and defensive activities.

The next step is to derive the first-order conditions characterizing a competitive market equilibrium, where we find that competitive firms with free access to environmental resources will continue to engage in polluting activities until the marginal return is zero, that is, until $\partial X/\partial E = 0$. We thus obtain the familiar result that because of their disregard for the external costs that they impose on others, polluting agents will engage in socially excessive levels of polluting activities.

The policy implication of this result is

[3] This highly simplifed model, although useful for our analytical purposes, admittedly fails to encompass the complexity of the natural environment. There is an important literature in environmental economics that develops the "materials-balance" approach to environmental analysis (see Kneese, Robert Ayres, and Ralph d'Arge 1970; Karl-Göran Mäler 1974, 1985). This approach introduces explicitly the flows of environmental resources and the physical laws to which they are subject. Some of these matters will figure in the discussion that follows.

clear. Polluting agents need to be confronted with a "price" equal to the marginal external cost of their polluting activities to induce them to internalize at the margin the full social costs of their pursuits. Such a price incentive can take the form of the familiar "Pigouvian tax," a levy on the polluting agent equal to marginal social damage. In the preceding formulation, the tax would be set equal to the expression in equation (5). Note further that the unit tax (or "effluent fee") must be attached *directly* to the polluting activity, not to some related output or input. Assuming some substitution among inputs in production, the Pigouvian tax would take the form of a levy per unit of waste emissions into the environment—not a tax on units of the firm's output or an input (e.g., fossil fuel associated with pollution).[4]

The derivation of the first-order conditions characterizing utility-maximizing behavior by individuals yields a second result of interest. Inasmuch as defensive activities in the model provide only private benefits, we find that individual maximizing behavior will satisfy the first-order conditions for Pareto efficiency for such activities. Since they are confronted with a given price for each input, individuals will allocate their spending so that a marginal dollar yields the same increment to utility whether it is spent on consumption goods or defensive activities. There is no need for any extra inducement to achieve efficient levels of defensive activities.

Although this is quite straightforward, there are a couple of matters requiring further comment. First, the Pigouvian solution to the problem of externalities has been the subject of repeated attack along Coasian lines. The Ronald Coase (1960) argument is that in the absence of transactions costs and strategic behavior, the distortions associated with externalities will be resolved through voluntary bargains struck among the interested parties. No further inducements (such as a Pigouvian tax) are needed in this setting to achieve an efficient outcome. In fact, as Ralph Turvey (1963) showed, the introduction of a Pigouvian tax in a Coasian setting will itself be the source of distortions. Our sense, however, is that the Coasian criticism is of limited relevance to most of the major pollution problems. Since most cases of air and water pollution, for example, involve a large number of polluting agents and/or victims, the likelihood of a negotiated resolution of the problem is small—transactions costs are simply too large to permit a Coasian resolution of most major environmental problems. It thus seems to us that a Nash or "independent adjustment" equilibrium is, for most environmental issues, the appropriate analytical framework. In this setting, the Pigouvian cure for the externality malady is a valid one.[5]

Second, there has been no mention of any compensation to the victims of externalities. This is an important point—and a source of some confusion in the literature—for Coase and others have suggested that in certain circumstances compensation of victims for damages by polluting agents is necessary for an efficient outcome. As the mathematics makes clear, this is not the case for our model above. In fact, the result is even stronger: compensation of victims is not permissible (except through lump-sum transfers). Where victims have the opportunity to engage in defensive (or "averting") activities to mitigate the effects of the pollution from which they

[4] Where it is not feasible to monitor emissions directly, the alternative may be to tax an input or output that is closely related to emissions of the pollutant. This gives rise to a standard sort of second-best problem in taxation.

[5] For comparative analyses of the bargaining and tax approaches to the control of externalities, see Daniel Bromley (1986), and Jonathan Hamilton, Eytan Sheshinski, and Steven Slutsky (1989).

suffer, compensation cannot be allowed. For if victims are compensated for the damages they suffer, they will no longer have the incentive to undertake efficient levels of defensive measures (e.g., to locate away from polluting factories or employ various sorts of cleansing devices). As is clear in the preceding formulation, the benefits from defensive activities are private in nature (they accrue solely to the victim that undertakes them) and, as a result, economic efficiency requires no incentives other than the benefits they confer on the victim.[6]

The basic theoretical result then (subject to some qualifications to be discussed later) is that the efficient resolution of environmental externalities calls for polluting agents to face a cost at the margin for their polluting activities equal to the value of the damages they produce and for victims to select their own levels of defensive activities with no compensation from polluters. We consider next some policy alternatives for achieving this result.

B. *The Choice Among Policy Instruments*[7]

The analysis in the preceding section has run in terms of a unit tax on polluting activities. There are, however, other approaches to establishing the proper economic incentives for abatement activities. Two alternative policy instruments have received extensive attention in the literature: unit subsidies and marketable emission permits.

It was recognized early on that a subsidy per unit of emissions reduction could establish the same incentive for abatement activity as a tax of the same magnitude per unit of waste discharges: a subsidy of 10 cents per pound of sulfur emissions reductions creates the same opportunity cost for sulfur emissions as a tax of 10 cents per unit of sulfur discharges. From this perspective, the two policy instruments are equivalent: the regulator can use either the stick or the carrot to create the desired incentive for abatement efforts.

It soon became apparent that there are some important asymmetries between these two policy instruments (e.g., Morton Kamien, Nancy L. Schwartz, and F. Trenery Dolbear 1966; D. Bramhall and Edwin Mills 1966; Kneese and Bower 1968). In particular, they have quite different implications for the profitability of production in a polluting industry: subsidies increase profits, while taxes decrease them. The policy instruments thus have quite different implications for the long-run, entry-exit decisions of firms. The subsidy approach will shift the industry supply curve to the right and result in a larger number of firms and higher industry output, while the Pigouvian tax will shift the supply curve to the left with a consequent contraction in the size of the industry. It is even conceivable that the subsidy approach could result in an increase in the total amount of pollution (Baumol and Oates 1988, ch. 14; Stuart Mestelman 1982; Robert Kohn 1985).

The basic point is that there is a further condition, an entry-exit condition, that

[6] There may, of course, exist cases where defensive activities have "publicness" properties—where the actions of one victim to defend himself against pollution also provide defense for others. In such cases, there is clearly an externality present so that individual maximizing behavior will not yield the efficient levels of defensive activities. For a careful and thorough examination of defensive activities, see Richard Butler and Michael Maher (1986). Incidentally, the general issue of compensation of victims from pollution obviously has much in common with the moral hazard problem in insurance.

[7] A further policy instrument not discussed in this section but with some potentially useful applications in environmental policy is deposit-refund systems (Peter Bohm 1981). Such systems can shift some of the responsibility for monitoring and effectively place the burden of proof on the source. For under this approach, the source, to recoup its deposit, must demonstrate that its activities have not damaged the environment. See Robert Costanza and Charles Perrings (1990) for a policy proposal under this rubric.

long-run equilibrium must satisfy for an efficient outcome (William Schulze and d'Arge 1974; Robert Collinge and Oates 1982; Daniel Spulber 1985). To obtain the correct number of firms in the long run, it is essential that firms pay not only the cost of the marginal damages of their emissions, but also the total cost arising from their waste emissions. Only if firms bear the total cost of their emissions will the prospective profitability of the enterprise reflect the true social net benefit of entry and exit into the industry.[8] In sum, unit subsidies are not a fully satisfactory alternative to Pigouvian taxes (Donald Dewees and W. A. Sims 1976).

In contrast, in a world of perfect knowledge, marketable emission permits are, in principle, a fully equivalent alternative to unit taxes. Instead of setting the proper Pigouvian tax and obtaining the efficient quantity of waste discharges as a result, the environmental authority could issue emission permits equal in the aggregate to the efficient quantity and allow firms to bid for them. It is not hard to show that the market-clearing price will produce an outcome that satisfies the first-order conditions both for efficiency in pollution abatement activities in the short run and for entry-exit decisions in the long run. The regulator can, in short, set either "price" or "quantity" and achieve the desired result.[9]

This symmetry between the price and quantity approaches is, however, critically dependent upon the assumption of perfect knowledge. In a setting of imperfect information concerning the marginal benefit and cost functions, the outcomes under the two approaches can differ in important ways.

C. *Environment Policy Under Uncertainty*

In a seminal paper, Martin Weitzman (1974) explored this asymmetry between price and quantity instruments and produced a theorem with important policy implications. The theorem establishes the conditions under which the expected welfare gain under a unit tax exceeds, is equal to, or falls short of that under a system of marketable permits (quotas). In short, the theorem states that in the presence of uncertainty concerning the costs of pollution control, the preferred policy instrument depends on the *relative* steepness of the marginal benefit and cost curves.[10]

[8] In an intriguing qualification to this argument, Martin Bailey (1982) has shown that not only subsidies to polluters, but also compensation to victims, will result in no distortions in resource use where benefits and damages are capitalized into site rents. For a discussion of the Bailey argument, see Baumol and Oates (1988, pp. 230–34). In another interesting extension, Gene Mumy (1980) shows that a combined charges-subsidy scheme can be fully efficient. Under this approach, sources pay a unit tax for emissions above some specified baseline, but receive a unit subsidy for emissions reductions below the baseline. The key provision is that the right to subsidy payments is limited to existing firms (i.e., new sources have a baseline of zero) and that this right can either be sold or be exercised even if the firm chooses to exit the industry. For a useful development of Mumy's insight, see John Pezzey (1990).

[9] The discussion glosses over some quite troublesome matters of implementation. For example, the effects of the emissions of a particular pollutant on ambient air or water quality will often depend importantly on the location of the source. In such cases, the optimal fee must be tailored to the damages per unit of emissions source-by-source. Or, alternatively, in a market for emission permits, the rate at which permits are traded among any two sources will vary with the effects of their respective emissions. In such a setting, programs that treat all sources uniformly can forego significant efficiency gains (Eugene Seskin, Robert Anderson, and Robert Reid 1983; Charles Kolstad 1987). More on all this shortly.

[10] This result assumes linearity of the marginal benefit and cost functions over the relevant range and that the error term enters each function additively. Uncertainty in the benefits function, interestingly, is not enough in its own right to introduce any asymmetries; while it is the source of some expected welfare loss relative to the case of perfect information, there is no difference in this loss as between the two policy instruments. For useful diagrammatic treatments of the Weitzman analysis, see Zvi Adar and James Griffin (1976), Gideon Fishelson (1976), and Baumol and Oates (1988, ch. 5).

The intuition of the Weitzman proposition is straightforward. Consider, for example, the case where the marginal benefits curve is quite steep but marginal control costs are fairly constant over the relevant range. This could reflect some kind of environmental threshold effect where, if pollutant concentrations rise only slightly over some range, dire environmental consequences follow. In such a setting, it is clearly important that the environmental authority have a close control over the quantity of emissions. If, instead, a price instrument were employed and the authority were to underestimate the true costs of pollution control, emissions might exceed the critical range with a resulting environmental disaster. In such a case, the Weitzman theorem tells us, quite sensibly, that the regulator should choose the quantity instrument (because the marginal benefits curve has a greater absolute slope than the marginal cost curve).

Suppose, next, that it is the marginal abatement cost curve that is steep and that the marginal benefits from pollution control are relatively constant over the relevant range. The danger here is that because of imperfect information, the regulatory agency might, for example, select an overly stringent standard, thereby imposing large, excessive costs on polluters and society. Under these circumstances, the expected welfare gain is larger under the price instrument. Polluters will not get stuck with inordinately high control costs, since they always have the option of paying the unit tax on emissions rather than reducing their discharges further.

The Weitzman theorem thus suggests the conditions under which each of these two policy instruments is to be preferred to the other. Not surprisingly, an even better expected outcome can be obtained by using price and quantity instruments in tandem. As Marc Roberts and Michael Spence (1976) have shown, the regulator can set the quantity of permits at the level that equates expected marginal benefits and costs and then offer a subsidy for emissions reductions in excess of those required by the permits and also a unit tax to provide a kind of "escape hatch" in case control costs turn out to be significantly higher than anticipated. In this way, a combination of price and quantity instruments can, in a setting of imperfect information, provide a larger expected welfare gain than an approach relying on either policy instrument alone (see also Weitzman 1978).[11]

D. *Market Imperfections*

The efficiency properties of the policy measures we have discussed depend for their validity upon a perfectly competitive equilibrium. This is a suspect assumption, particularly since many of the major polluters in the real world are large firms in heavily concentrated industries: oil refineries, chemical companies, and auto manufacturers. This raises the issue of the robustness of the results to the presence of large firms that are not price takers in their output markets.

James Buchanan (1969) called attention to this issue by showing that the imposition of a Pigouvian tax on a monopolist could conceivably reduce (rather than raise) social welfare. A monopolist restricts output below socially optimal levels, and a tax on waste emissions will lead to yet further contractions in output. The net effect is unclear. The welfare gains from reduced pollution must be offset against the losses from the reduced output of the monopolist.

The first-best response to this conun-

[11] Butler and Maher (1982) show that in a setting of economic growth, the shifts in the marginal damage and marginal control cost schedules are likely to be such as to increase substantially the welfare loss from a fixed fee system relative to that from a system of marketable permits.

drum is clear. The regulatory authority should introduce two policy measures: a Pigouvian tax on waste emissions plus a unit subsidy to output equal to the difference between marginal cost and marginal revenue at the socially optimal level of output. Since there are two distortions, two policy instruments are required for a full resolution of the problem. Environmental regulators, however, are unlikely to have the authority (or inclination) to subsidize the output of monopolists. In the absence of such subsidies, the agency might seek to determine the second-best tax on effluents. Dwight Lee (1975) and Andy Barnett (1980) have provided the solution to this problem by deriving formally the rule for the second-best tax on waste emissions. The rule calls for a unit tax on emissions that is somewhat less than the unit tax on a perfectly competitive polluter (to account for the output effect of the tax):

$$t^* = t_c - \left| (P - MC)\frac{dX}{dE} \right| \qquad (7)$$

Equation (7) indicates that the second-best tax per unit of waste emissions (t^*) equals the Pigouvian tax on a perfectly competitive firm (t_c) *minus* the welfare loss from the reduced output of the monopolist expressed as the difference between the value of a marginal unit of output and its cost times the reduction in output associated with a unit decrease in waste emissions. It can be shown by the appropriate manipulation of (7) that the second-best tax on the monopolist varies directly with the price elasticity of demand. The rationale is clear: where demand is more price elastic, the price distortion (i.e., the divergence between price and marginal cost) tends to be smaller so that the tax on effluent need not be reduced by so much as where demand is more price inelastic.

It seems unlikely, however, that the regulator will have either the information needed or the authority to determine and impose a set of taxes on waste emissions that is differentiated by the degree of monopoly power. Suppose that the environmental authority is constrained to levying a uniform tax on waste discharges and suppose that it determines this tax in a Pigouvian manner by setting it equal to marginal social damages from pollution, completely ignoring the issue of market imperfections. How badly are things likely to go wrong? Oates and Diana Strassmann (1984) have explored this question and, using some representative values for various parameters, conclude that the complications from monopoly and other noncompetitive elements are likely to be small in magnitude; the losses from reduced output will typically be "swamped" by the allocative gains from reduced pollution. They suggest that, based on their estimates, it is not unreasonable simply to ignore the matter of incremental output distortions from effluent fees.[12] Their analysis suggests further that the failure of polluting agents to minimize costs because of more complex objective functions (a la Williamson), public agencies of the Niskanan sort, or because of regulatory constraints on profits need not seriously undermine the case for pricing incentives for pollution control. This subject needs further study, especially since many of the principal participants in the permit market for trading sulfur allowances under the new Amendments to the Clean Air Act will be regulated firms.

E. *On the Robustness of the Pigouvian Prescription: Some Further Matters*

Although the literature has established certain basic properties of the Pi-

[12] For more on this issue, see Peter Asch and Joseph Seneca (1976), Walter Misiolek (1980), and Burrows (1981).

gouvian solution to the problem of externalities, there are some remaining troublesome matters. One concerns the information requirements needed to implement the approach. Developing reliable measures of the benefits and costs of environmental amenities is, as we shall see shortly, a difficult undertaking. To determine the appropriate Pigouvian levy, moreover, we not only need measures of existing damages and control costs, but we need to develop measures of the incremental costs and benefits over a substantial range. For the proper Pigouvian levy is not a tax equal to marginal social damages at the *existing* level of pollution; it is a tax equal to marginal damages *at the optimal outcome*. We must effectively solve for the optimal level of pollution to determine the level of the tax. As an alternative, we might set the tax equal to the existing level of damages and then adjust it as levels of pollution change in the expectation that such an iterative procedure will lead us to the socially optimal outcome. But even this is not guaranteed (Baumol and Oates 1988, ch. 7).

There is, moreover, a closely related problem. In the discussion thus far, we have examined solely the first-order conditions for efficient outcomes; we have not raised the issue of satisfying any second-order conditions. As Baumol and David Bradford (1972) have shown, this is a particularly dangerous omission in the presence of externalities.[13] In fact, they demonstrate that if a detrimental externality is of sufficient strength, it *must* result in a breakdown of the convexity-concavity conditions required for an optimal outcome. As a result, there may easily exist a multiplicity of local maxima from which to choose—with no simple rule to determine the first-best outcome.[14] Under such circumstances, equilibrium prices may tell us nothing about the efficiency of current output or the direction in which to seek improvement.

There are thus reasons for some real reservations concerning the direct application of the Pigouvian analysis to the formulation of environmental policy. It is to this issue that we turn next.

III. *The Design and Implementation of Environmental Policy*

A. *Introduction: From Theory to Policy*

Problems of measurement and the breakdown of second-order conditions (among other things) constitute formidable obstacles to the determination of a truly first-best environmental policy. In response to these obstacles, the literature has explored some second-best approaches to policy design that have appealing properties. Moreover, they try to be more consistent with the procedures and spirit of decision making in the policy arena.

Under these approaches, the determination of environmental policy is taken to be a two-step process: first, standards or targets for environmental quality are set, and, second, a regulatory system is designed and put in place to achieve these standards. This is often the way environmental decision making proceeds. Under the Clean Air Act, for example, the first task of the EPA was to set standards in the form of maximum

[13] See also Richard Portes (1970), David Starrett (1972), J. R. Gould (1977), and Burrows (1986).

[14] This problem is further compounded by the presence of defensive activities among victims of pollution. The interaction among abatement measures by polluters and defensive activities by victims can be a further source of nonconvexities (Hirofumi Shibata and Steven Winrich 1983; Oates 1983). Yet another source of nonconvexities can be found in the structure of subsidy programs that offer payments for emissions reductions to firms in excess of some minimum size (Raymond Palmquist 1990).

permissible concentrations of the major air pollutants. The next step was to design a regulatory plan to attain these standards for air quality.

In such a setting, systems of economic incentives can come into play in the second stage as effective regulatory instruments for the achievement of the predetermined environmental standards. Baumol and Oates (1971) have described such a system employing effluent fees as the "charges and standards" approach. But marketable permit systems can also function in this setting—a so-called "permits and standards" approach (Baumol and Oates 1988, ch. 12) [15]

The chief appeal of economic incentives as the regulatory device for achieving environmental standards is the large potential cost-savings that they promise. There is now an extensive body of empirical studies that estimate the cost of achieving standards for environmental quality under existing command-and-control (CAC) regulatory programs (e.g., Scott Atkinson and Donald Lewis 1974; Seskin, Anderson, and Reid 1983; Alan Krupnick 1983; Adele Palmer et al. 1980; Albert McGartland 1984). These are typically programs under which the environmental authority prescribes (often in great detail) the treatment procedures that are to be adopted by each source. The studies compare costs under CAC programs with those under a more cost effective system of economic incentives. The results have been quite striking: they indicate that control costs under existing programs have often been several times the least-cost levels. (See Thomas Tietenberg 1985, ch. 3, for a useful survey of these cost studies.)

The source of these large cost savings is the capacity of economic instruments to take advantage of the large differentials in abatement costs across polluters. The information problems confronting regulators under the more traditional CAC approaches are enormous—and they lead regulators to make only very rough and crude distinctions among sources (e.g., new versus old firms). In a setting of perfect information, such problems would, of course, disappear. But in the real world of imperfect information, economic instruments have the important advantage of economizing on the need for the environmental agency to acquire information on the abatement costs of individual sources. This is just another example of the more general principles concerning the capacity of markets to deal efficiently with information problems.[16]

The estimated cost savings in the studies cited above result from a more cost effective allocation of abatement efforts within the context of existing control technologies. From a more dynamic perspective, economic incentives promise additional gains in terms of encouraging the development of more effective and less costly abatement techniques. As John Wenders (1975) points out in this context, a system that puts a value on any discharges remaining after control (such as a system of fees or marketable permits) will provide a greater incentive to R&D efforts in control technology than will a regulation that specifies some given level of discharges (see also Wesley Magat 1978, and Scott Milliman and Raymond Prince 1989).

[15] This is admittedly a highly simplified view of the policy process. There is surely some interplay in debate and negotiations between the determination of standards and the choice of policy instruments. More broadly, there is an emerging literature on the political economy of environmental policy that seeks to provide a better understanding of the process of instrument choice—see, for example, McCubbins, Noll, and Weingast (1989), and Robert Hahn (1990).

[16] There is also an interesting literature on incentive-compatible mechanisms to obtain abatement cost information from polluters—see, for example, Evan Kwerel (1977).

B. *The Choice of Policy Instruments Again*[17]

Some interesting issues arise in the choice between systems of effluent fees and marketable emission permits in the policy arena (John H. Dales 1968; Dewees 1983; David Harrison 1983). There is, of course, a basic sense in which they are equivalent: the environmental authority can, in principle, set price (i.e., the level of the effluent charge) and then adjust it until emissions are reduced sufficiently to achieve the prescribed environmental standard, or, alternatively, issue the requisite number of permits directly and allow the bidding of polluters to determine the market-clearing price.

However, this basic equivalence obscures some crucial differences between the two approaches in a policy setting; they are by no means equivalent policy instruments from the perspective of a regulatory agency. A major advantage of the marketable permit approach is that it gives the environmental authority direct control over the quantity of emissions. Under the fee approach, the regulator must set a fee, and if, for example, the fee turns out to be too low, pollution will exceed permissible levels. The agency will find itself in the uncomfortable positio· of having to adjust and readjust the fee to ensure that the environmental standard is attained. Direct control over quantity is to be preferred since the standard itself is prescribed in quantity terms.

This consideration is particularly important over time in a world of growth and inflation. A nominal fee that is adequate to hold emissions to the requisite levels at one moment in time will fail to do so later in the presence of economic growth and a rising price level. The regulatory agency will have to enact periodic (and unpopular) increases in effluent fees. In contrast, a system of marketable permits automatically accommodates itself to growth and inflation. Since there can be no change in the aggregate quantity of emissions without some explicit action on the part of the agency, increased demand will simply translate itself into a higher market-clearing price for permits with no effects on levels of waste discharges.

Polluters (that is, *existing* polluters), as well as regulators, are likely to prefer the permit approach because it can involve lower levels of compliance costs. If the permits are auctioned off, then of course polluters must pay directly for the right to emit wastes as they would under a fee system. But rather than allocating the permits by auction, the environmental authority can initiate the system with a one-time distribution of permits to existing sources—free of charge. Some form of "grandfathering" can be used to allocate permits based on historical performance. Existing firms thus receive a marketable asset, which they can then use either to validate their own emissions or sell to another polluter.[18] And finally, the permit approach has some advantages in terms of familiarity. Regulators have long-standing experience with permits, and it is a much less radical change to make permits effectively transferable than to introduce a wholly new system of regulation based on effluent fees. Mar-

[17] For a useful, comprehensive survey of the strengths and weaknesses of alternative policy instruments for pollution control, see Bohm and Clifford Russell (1985).

[18] In an interesting simulation study, Randolph Lyon (1982) finds that the cost of permits to sources under an auction system can be quite high; for one of the auction simulations, he finds that aggregate payments for permits will exceed treatment costs. Lyon's results thus suggest potentially large gains to polluting firms from a free distribution of permits instead of their sale through an auction. These gains, of course, are limited to current sources. Polluting firms that arrive on the scene at a later date will have to purchase permits from existing dischargers.

ketable permits thus have some quite appealing features to a regulatory agency—features that no doubt explain to some degree the revealed preference for this approach (in the U.S. at least) over that of fees.

Effluent charges have their own appeal. They are sources of public revenue, and, in these days of large budget deficits, they promise a new revenue source to hard-pressed legislators. From an economic perspective, there is much to be said for the substitution of fees for other sources of revenues that carry sizable excess burdens (Lee and Misiolek 1986). In a study of effluent charges on emissions of particulates and sulfur oxides from stationary sources into the atmosphere. David Terkla (1984) estimates, based on assumed levels of tax rates, that revenues in 1982 dollars would range from \$1.8 to \$8.7 billion and would, in addition, provide substantial efficiency gains (\$630 million to \$3.05 billion) if substituted for revenues from either the federal individual income tax or corporation income tax.

Moreover, the charges approach does not depend for its effectiveness on the development of a smoothly functioning market in permits. Significant search costs, strategic behavior, and market imperfections can impede the workings of a permit market (Hahn 1984; Tietenberg 1985, ch. 6). In contrast, under a system of fees, no transfers of permits are needed—each polluter simply responds directly to the incentive provided by the existing fee. There may well be circumstances under which it is easier to realize a cost-effective pattern of abatement efforts through a visible set of fees than through the workings of a somewhat distorted permit market. And finally, there is an equity argument in favor of fees (instead of a free distribution of permits to sources). The Organization for Economic Cooperation and Development (OECD), for example, has adopted the "Polluter Pays Principle" on the grounds that those who use society's scarce environmental resources should compensate the public for their use.

There exists a large literature on the design of fee systems and permit markets to attain predetermined levels of environmental quality. This work addresses the difficult issues that arise in the design and functioning of systems of economic incentives—issues that receive little or only perfunctory attention in the purely theoretical literature but are of real concern in the operation of actual policy measures. For example, there is the tricky matter of spatial differentiation. For most pollutants, the effect of discharges on environmental quality typically has important spatial dimensions: the specific location of the source dictates the effects that its emissions will have on environmental quality at the various monitoring points. While, in principle, this simply calls for differentiating the effluent fee according to location, in practice this is not so easy. The regulatory agency often does not have the authority or inclination to levy differing tax rates on sources according to their location. Various compromises including the construction of zones with uniform fees have been investigated (Tietenberg 1978; Seskin, Anderson, and Reid 1983; Kolstad 1987).

Similarly, problems arise under systems of transferable permits where (as is often the case) the effects of the emissions of the partners to a trade are not the same. (The seminal theoretical paper is W. David Montgomery 1972.) Several alternatives have been proposed including zoned systems that allow trades only among polluters within the specified zones, ambient permit systems under which the terms of trade are determined by the relative effects of emissions at binding monitors, and the pollution-offset system under which trades are subject to the constraint of no violations of the prevailing standard at any point in the area (Atkinson and Tietenberg 1982; Atkinson and Lewis 1974; Hahn and Noll 1982; Krupnick, Oates, and Eric Van de Verg 1983; McCartland and Oates 1985; McCartland 1988; Tietenberg 1980, 1985; Walter Spofford 1984; Baumol and Oates 1988, ch. 12). For certain pollutants, these studies make clear that a substantial portion of the cost-savings from economic-incentive approaches will be lost if spatial differentiation is not, at least to some degree, built into the program (Robert Mendelsohn 1986).

The actual design of systems of economic incentives inevitably involves some basic compromises to accommodate the range of complications to the regulatory problem (Albert Nichols 1984). It is instructive to see how some of these issues have been dealt with in practice.

C. *Experience with Economic Incentives for Environmental Management*[19]

In the United States proposals for effluent fees have met with little success; however, there has been some limited experience with programs of marketable permits for the regulation of air and water quality. In Europe, the experience (at least until quite recently) has been the reverse: some modest use of effluent charges but no experience with transferable permits. We shall provide in this section a brief summary of these measures along with some remarks on their achievements and failures.

Largely for the reasons mentioned in the preceding section, policy makers in the U.S. have found marketable permits preferable to fees as a mechanism for providing economic incentives for pollution control.[20] The major program of this genre is the EPA's Emission Trading Program for the regulation of air quality. But there are also three other programs worthy of note: the Wisconsin system of Transferable Discharge Permits (TDP) for the management of water quality, the lead trading program (known formally as "interrefinery averaging"), and a recent program for the trading of rights for phosphorus discharges into the Dillon Reservoir in Colorado.[21]

By far the most important of these programs in terms of scope and impact, Emissions Trading has undergone a fairly complicated evolution into a program that has several major components. Under the widely publicized "Bubble" provision, a plant with many sources of emissions of a particular air pollutant is subjected to an overall emissions limitation. Within this limit, the managers of the plant have the flexibility to select a set of controls consistent with the aggregate limit, rather than conforming to specified treatment procedures for each source of discharges with the plant. Under the "Netting" provision, firms can avoid stringent limitations on new sources

[19] The OECD (1989) has recently provided a useful "catalog" and accompanying discussion of the use of economic incentives for environmental protection in the OECD countries.

[20] One case in which there has been some use of fees in the U.S. is the levying of charges on industrial emissions into municipal waste treatment facilities. In some instances these charges have been based not only on the quantity but also on the strength or quality of the effluent. The charges are often related to "average" levels of discharges and have had as their primary objective the raising of funds to help finance the treatment plants. Their role as an economic incentive to regulate levels of emissions has apparently been minor (see James Boland 1986; Baumol and Oates 1979, pp. 258–63). There are also a variety of taxes on the disposal of hazardous wastes, including land disposal taxes in several states.

[21] Tietenberg's book (1985) is an excellent, comprehensive treatment of the Emissions Trading Program. Robert Hahn and Gordon Hester have provided a series of recent and very valuable descriptions and assessments of all four of these programs of marketable permits. See Hahn and Hester (1989a, 1989b), and Hahn (1989). For analyses of the Wisconsin TDP system, see William O'Neil (1983), and O'Neil et al. (1983).

of discharges by reducing emissions from other sources of the pollutant within the facility. Hahn and Hester (1989b) report that to date there have been over 100 approved Bubble transactions in the U.S. and a much larger number of Netting "trades" (somewhere between 5,000 and 12,000). The estimated cost savings from these trades have been quite substantial; although the estimates exhibit a very wide range, the cost savings probably amount to several billion dollars.

There are provisions under Emissions Trading for external trades across firms—mainly under the Offset provision which allows new sources in nonattainment areas to "offset" their new emissions with reductions in discharges by existing sources. Offsets can be obtained through either internal (within plant) or external trades. Hahn and Hester (1989b) indicate that there have been about 2,000 trades under the Offset policy; only about 10 percent of them have been external trades—the great bulk of offsets have been obtained within the plant or facility.

Emissions Trading, as a whole, receives mixed marks. It has significantly increased the flexibility with which sources can meet their discharge limitations—and this has been important for it has allowed substantial cost savings. The great majority of the trades, however, have been internal ones. A real and active market in emissions rights involving different firms has not developed under the program (in spite of the efforts of an active firm functioning as a broker in this market). This seems to be largely the result of an extensive and complicated set of procedures for external trades that have introduced substantial levels of transactions costs into the market and have created uncertainties concerning the nature of the property rights that are being acquired. In addition, the program has been grafted onto an elaborate set of command-and-control style regulations which effectively prohibit certain kinds of trades. Many potentially profitable trades simply have not come to pass.[22]

Likewise, the experience under the Wisconsin TDP system has involved little external trading. The program establishes a framework under which the rights to BOD discharges can be traded among sources. Since the program's inception in 1981 on the Fox River, there has been only one trade: a paper mill which shifted its treatment activities to a municipal wastewater treatment plant transferred its rights to the municipal facility. The potential number of trades is limited since there are only about twenty major sources (paper mills and municipal waste treatment plants) along the banks of the river. But even so, preliminary studies (O'Neil 1983; O'Neil et al. 1983) indicated several potentially quite profitable trades involving large cost savings. A set of quite severe restrictions appears to have discouraged these transfers of permits. Trades must be justified on the basis of "need"—and this does not include reduced costs! Moreover, the traded rights are granted only for the term of the seller's discharge permit (a maximum period of five years) with no assurance that the rights will be renewed. The Wisconsin experience seems to be one in which the conditions needed for the emergence of a viable market in discharge permits have not been established.

In contrast, EPA's "interrefinery averaging" program for the trading of lead rights resulted in a very active market over the relatively short life of the program. Begun in 1982, the program allowed refiners to trade the severely lim-

[22] In an interesting analysis of the experience with Emissions Trading, Roger Raufer and Stephen Feldman (1987) argue that some of the obstacles to trading could be circumvented by allowing the leasing of rights.

ited rights to lead additives to gasoline. The program expired in 1986, although refiners were permitted to make a use of rights that were "banked" through 1987. Trading became brisk under the program: over the first half of 1987, for example, around 50 percent of all lead added to gasoline was obtained through trades of lead rights, with substantial cost savings reported from these trades. Although reliable estimates of cost-savings for the lead-trading program are not available, Hahn and Hester (1989b) surmise that these savings have run into the hundreds of millions of dollars. As they point out, the success of the program stemmed largely from the absence of a large body of restrictions on trades: refiners were essentially free to trade lead rights and needed only to submit a quarterly report to EPA on their gasoline production and lead usage. There were, moreover, already well established markets in refinery products (including a wide variety of fuel additives) so that refinery managers had plenty of experience in these kinds of transactions.[23]

Finally, there is an emerging program in Colorado for the trading of rights to phosphorous discharges into the Dillon Reservoir. This program is noteworthy in that among those that we have discussed, it is the only one to be designed and introduced by a local government. The plan embodies few encumbrances to trading; the one major restriction is a 2:1 trading ratio for point/nonpoint trading, introduced as a "margin of safety" because of uncertainties concerning the effectiveness of nonpoint source controls. The program is still in its early stages: although no trades have been approved, some have been requested.

The U.S. experience with marketable permits is thus a limited one with quite mixed results. In the one case where the market was allowed to function free of heavy restrictions, vigorous trading resulted with apparently large cost savings. In contrast, under Emissions Trading and the Wisconsin TDP systems, stringent restrictions on the markets for trading emissions rights appear to have effectively increased transaction costs and introduced uncertainties, seriously impeding the ability of these markets to realize the potentially large cost savings from trading. Even so, the cost savings from Emissions Trading (primarily from the Netting and Bubble provisions) have run into several billion dollars. Finally, it is interesting that these programs seem not to have had any significant and adverse environmental effects; Hahn and Hester (1989a) suggest that their impact on environmental quality has been roughly "neutral."

In light of this experience, the prospects, we think, appear favorable for the functioning of the new market in sulfur allowances that is being created under the 1990 Amendments to the Clean Air Act. This measure, designed to address the acid rain problem by cutting back annual sulfur emissions by 10 million tons, will permit affected power plants to meet their emissions reduction quotas by whatever means they wish, including the purchase of "excess" emissions reductions from other sources. The market area for this program is the nation as a whole so that there should be a large number of potential participants in the market. At this juncture, plans for the structure and functioning of the market do not appear to contain major limitations that would impede trading in the sulfur allowances. There remains, however, the possibility that state governors or public utility commissions will introduce some restrictions. There is the further concern that regulated firms may not behave

[23] We should also note that various irregularities and illegal procedures were discovered in this market—perhaps because of lax oversight.

in a strictly cost-minimizing fashion, thereby compromising some of the cost-effectiveness properties of the trading scheme. But as we suggested earlier, this may not prove to be a serious distortion.

The use of effluent fees is more prevalent in Europe where they have been employed extensively in systems of water quality management and to a limited extent for noise abatement (Ralph Johnson and Gardner Brown, Jr. 1976; Bower et al. 1981; Brown and Hans Bressers 1986; Brown and Johnson 1984; Tietenberg 1990). There are few attempts to use them for the control of air pollution. France, Germany, and the Netherlands, for example, have imposed effluent fees on emissions of various water pollutants for over two decades. It should be stressed that these fee systems are not pure systems of economic incentives of the sort discussed in economics texts. Their primary intent has not been the regulation of discharges, but rather the raising of funds to finance projects for water quality management. As such, the fees have typically been low and have tended to apply to "average" or "expected" discharges rather than to provide a clear cost signal at the margin. Moreover, the charges are overlaid on an extensive command-and-control system of regulations that mute somewhat further their effects as economic incentives.

The Netherlands has one of the oldest and most effectively managed systems of charges—and also the one with relatively high levels of fees. There is some evidence suggesting that these fees have, in fact, had a measurable effect in reducing emissions. Some multiple regression work by Hans Bressers (1983) in the Netherlands and surveys of industrial polluters and water board officials by Brown and Bressers (1986) indicate that firms have responded to the charges with significant cutbacks in discharges of water borne pollutants.

In sum, although there is some experience with systems of fees for pollution control, mainly of water pollution, these systems have not, for the most part, been designed in the spirit of economic incentives for the regulation of water quality. Their role has been more that of a revenue device to finance programs for water quality management.

These systems, it is worth noting, have addressed almost exclusively so-called "point-source" polluters. Non-point source pollution (including agricultural and urban runoff into waterways) has proved much more difficult to encompass within systems of charges or permits. Winston Harrington, Krupnick, and Henry Peskin (1985) provide a useful overview of the potential role for economic incentives in the management of non-point sources. This becomes largely a matter of seeking out potentially effective second-best measures (e.g., fees on fertilizer use), since it is difficult to measure and monitor "discharges" of pollutants from these sources. Kathleen Segerson (1988) has advanced an ingenious proposal whereby such sources would be subject to a tax (or subsidy payment) based, not on their emissions, but on the observed level of environmental quality; although sources might find themselves with tax payments resulting from circumstances outside their control (e.g., adverse weather conditions), Segerson shows that such a scheme can induce efficient abatement and entry/exit behavior on the part of non-point sources.

D. *Legal Liability as an Economic Instrument for Environmental Protection*

An entirely different approach to regulating sources is to rely on legal liability for damages to the environment. Although we often do not include this approach under the heading of economic instruments, it is clear that a system of "strict liability," under which a source is financially responsible for damages, embodies important economic incentives.[24] The imposition of such liability effectively places an "expected price" on polluting activities. The ongoing suits, for example, following upon the massive Exxon-Valdez oil spill suggest that such penalties will surely exert pressures on potential polluters to engage in preventive measures.

Under this approach, the environmental authority, in a setting of uncertainty, need not set the values of any price or quantity instruments; it simply relies on the liability rule to discipline polluters. Two issues are of interest here. The first is the capacity, in principle, for strict liability to mimic the effects of a Pigouvian tax. And the second is the likely effectiveness, in practice, of strict liability as a substitute for other forms of economic incentives. There is a substantial literature in the economics of the law that addresses these general issues and a growing number of studies that explore this matter in the context of environmental management (see, for example, Steven Shavell 1984a, 1984b; Segerson 1990).

It is clear that strict liability can, in principle, provide the source of potential damages with the same incentive as a Pigouvian tax. If a polluter knows that he will be held financially accountable for any damages his activities create, then he will have the proper incentive to seek methods to avoid these damages. Strict liability serves to internalize the external costs—just as does an appropriate tax. Strict liability is unlike a tax, however, in that it provides compensation to victims. The Pigouvian tax possesses an important asymmetry in a market sense: it is a charge to the polluter—but not a payment to the victim. And, as noted earlier, such payments to victims can result in inefficient levels of defensive activities. Strict liability thus does not get perfect marks on efficiency grounds, even in principle, for although it internalizes the social costs of the polluter, it can be a source of distortions in victims' behavior.

The more important concern, in practice, is the effectiveness of legal liability in disciplining polluter behavior. Even if the basic rule is an efficient one in terms of placing liability on the source of the environmental damage, the actual "price" paid by the source may be much less than actual damages because of imperfections in the legal system: failures to impose liability on responsible parties resulting from uncertainty over causation, statutes of limitation, or high costs of prosecution.[25] There is the further possibility of bankruptcy as a means of avoiding large payments for damages. The evidence on these matters is mixed (see Segerson 1990), but it seems to suggest that legal liability has functioned only very imperfectly.

An interesting area of application in the environmental arena involves various pieces of legislation that provide strict liability for damages from accidental spills of oil or leakage of hazardous wastes. The Comprehensive Environmental Responses, Compensation, and Liability Act (CERCLA) of 1980 and its later amendments (popularly known as "Superfund") are noteworthy for their broad potential applicability (Thomas Grigalunas and James Opaluch 1988). Such measures may well provide a useful framework for internalizing the external

[24] The major alternative to strict liability is a negligence rule under which a polluter is liable only if he has failed to comply with a "due standard of care" in the activity that caused the damages. Under strict liability, the party causing the damages is liable irrespective of the care exercised in the polluting activity.

[25] As one reviewer noted, in these times of heightened environmental sensitivity, liability determinations could easily exceed actual damages in some instances. However, this seems not to have happened in the recent Exxon-Valdez case. The case was settled out of court with Exxon agreeing to pay some $900 million over a period of several years. Some observers believe that this falls well short of the true damages from the Exxon-Valdez oil spill in Alaska.

costs of spills (Opaluch and Grigalunas 1984). In particular, the liability approach appears to have its greatest appeal in cases like those under Superfund where damages are infrequent events and for which monitoring the level of care a firm takes under conventional regulatory procedures would be difficult.[26]

E. *Environmental Federalism*

In addition to the choice of policy instrument, there is the important issue of the locus of regulatory authority. In the case of fees, for example, should a central environmental authority establish a uniform fee applicable to polluters in all parts of the nation or should decentralized agencies set fee levels appropriate to their own jurisdictions? U.S. environmental policy exhibits considerable ambivalence on this matter. Under the Clean Air Act in 1970, the U.S. Congress instructed the Environmental Protection Agency to set uniform national standards for air quality—maximum permissible concentrations of key air pollutants applicable to all areas in the country. But two years later under the Clean Water Act, the Congress decided to let the individual states determine their own standards (subject to EPA approval) for water quality. The basic question is "Which approach, centralized decision making or environmental federalism, is the more promising?"

Basic economic principles seem to suggest, on first glance, a straightforward answer to this question. Since the benefits and costs of reduced levels of most forms of pollution are likely to vary (and vary substantially) across different jurisdictions, the optimal level of effluent fees (or quantities of marketable permits) will also vary (Sam Peltzman and T. Nicolaus Tideman 1972). The first-best outcome must therefore be one in which fees or quantities of permits are set in accord with local circumstances, suggesting that an optimal regulatory system for pollution control will be a form of environmental federalism.

Some environmental economists have raised an objection to this general presumption. John Cumberland (1981), among others, has expressed the concern that in their eagerness to attract new business and jobs, state or local officials will tend to set excessively lax environmental standards—fees that are too low or quantities of permits that are too high. The fear is that competition among decentralized jurisdictions for jobs and income will lead to excessive environmental degradation. This, incidentally, is a line of argument that has appeared elsewhere in the literature on fiscal federalism under the title of "tax competition." The difficulty in assessing this objection to decentralized policy making is that there exists little systematic evidence on the issue; most of the evidence is anecdotal in character, and, until quite recently, there has been little theoretical work addressing the phenomenon of interjurisdictional competition.[27]

In a pair of recent papers, Oates and Robert Schwab (1988a, 1988b) have set forth a model of such competition in which "local" jurisdictions compete for a mobile national stock of capital using both tax and environmental policy instruments. Since the production functions

[26] A more complicated and problematic issue relates to the permission of the courts to sue under Superfund for damages from toxic substances using "the joint and several liability doctrine." Under this provision, *each* defendant is potentially liable for an amount up to the *entire* damage, irrespective of his individual contribution. For an analysis of this doctrine in the Superfund setting, see Tietenberg (1989).

[27] Two recent studies, one by Virginia McConnell and Schwab (1990), and the other by Timothy Bartik (1988c), find little evidence of strong effects of existing environmental regulations on the location decisions of firms within the U.S. This, of course, does not preclude the possibility that state and local officials, in *fear* of such effects, will scale down standards for environmental quality.

are neoclassical in character, an increase in a jurisdiction's capital stock raises the level of wages through an associated increase in the capital-labor ratio. In the model, local officials simultaneously employ two policy tools to attract capital: a tax rate on capital itself which can be lowered or even set negative (a subsidy) to raise the return to capital in the jurisdiction, and a level of allowable pollutant emissions (or, alternatively, an effluent fee). By increasing the level of permissible waste discharges either directly or by lowering the fee on emissions, the local authority increases the marginal product of capital and thereby encourages a further inflow of capital. The model thus involves two straightforward tradeoffs: one between wage income and tax revenues, and the other between wage income and local environmental quality. The analysis reveals that in a setting of homogeneous worker-residents making choices by simple majority rule, jurisdictions select the socially optimal levels of these two policy instruments. The tax rate on capital is set equal to zero, and the level of environmental quality is chosen so that the willingness to pay for a cleaner environment is equal to marginal abatement cost. The analysis thus supports the case for environmental federalism: decentralized policy making is efficient in the model.[28]

In one sense, this is hardly a surprising result. Since local residents care about the level of environmental quality, we should not expect that they would wish to push levels of pollution into the range where the willingness to pay to avoid environmental damage exceeds the loss in wage income from a cleaner environment. At the same time, this result is not immune to various "imperfections." If, for example, local governments are constrained constitutionally to use taxes on capital to finance various local public goods, then it is easy to show that not only will the tax rate on capital be positive, but officials will select socially excessive levels of pollution. Likewise, if Niskanen bureaucrats run the local public sector, they will choose excessively lax environmental standards as a mechanism to attract capital so as to expand the local tax base and public revenues. Finally, there can easily be conflicts among local groups of residents with differing interests (e.g., workers vs. nonworkers) that can lead to distorted outcomes (although these distortions may involve too little or too much pollution).

The basio model does at least suggest that there are some fundamental forces promoting efficient decentralized environmental decisions. If the regions selected for environmental decision making are sufficiently large to internalize the polluting effects of waste discharges, the case for environmental federalism has some force. Exploration of this issue is admittedly in its infancy—in particular, there is a pressing need for some systematic empirical study of the effects of "local" competition on environmental choices.[29]

F. *Enforcement Issues*

The great bulk of the literature on the economics of environmental regulation simply assumes that polluters comply with existing directives: they either keep their discharges within the prescribed limitation or, under a fee scheme, report accurately their levels of emissions and pay the required fees.

[28] Using an alternative analytical framework in which local jurisdictions "bid" against one another for polluting firms in terms of entry fees, William Fischel (1975) likewise finds that local competition produces an efficient outcome.

[29] For some other recent theoretical studies of interjurisdictional fiscal competition, see Jack Mintz and Henry Tulkens (1986), John Wilson (1986), David Wildasin (1989), and George Zodrow and Peter Mieszkowski (1986).

Sources, in short, are assumed *both* to act in good faith and to have full control over their levels of discharges so that violations of prescribed behavior do not occur.

Taking its lead from the seminal paper by Gary Becker (1968) on the economics of crime and punishment, a recent literature has addressed enforcement issues as they apply to environmental regulations.[30] As this literature points out, violations of environmental regulations can have two sources: a polluter can willfully exceed his discharge limitation (or under-report his emissions under a fee system) to reduce compliance costs *or* a stochastic dimension to discharges may exist so that the polluter has only imperfect control over his levels of emissions. In such a setting, the regulatory problem becomes a more complicated one. Not only must the regulatory agency set the usual policy parameters (emissions limitations or fees), but it must also decide upon an enforcement policy which involves both monitoring procedures and levels of fines for violations.

The early literature explored these enforcement issues in a wholly static framework. The seminal papers, for example, by Paul Downing and William Watson (1974) and by Jon Harford (1978), established a number of interesting results. Downing and Watson show that the incorporation of enforcement costs into the analysis of environmental policy suggests that optimal levels of pollution control will be less than when these costs are ignored. Harford obtains the especially interesting result that under a system of effluent fees, the level of *actual* discharges is independent both of the level of the fine for underreporting and of the probability of punishment (so long as the slope of the expected penalty function with respect to the size of the violation is increasing and the probability of punishment is greater than zero). The polluter sets the level of actual wastes such that marginal abatement cost equals the effluent fee—the efficient level! But he then, in general, underreports his discharges with the extent of underreporting varying inversely with the level of fines and the probability of punishment.

Arun Malik (1990) has extended this line of analysis to the functioning of systems of marketable permits. He establishes a result analogous to Harford's: under certain circumstances, noncompliant polluters will emit precisely the same level of wastes for a given permit price as that discharged by an otherwise identical compliant firm. The conditions, however, for this equivalence are fairly stringent ones. More generally, Malik shows that noncompliant behavior will have effects on the market-clearing price in the permit market—effects that will compromise to some extent the efficiency properties of the marketable permit system.

One implication of this body of work is the expectation of widespread noncompliance on the part of polluters. But as Harrington (1988) points out, this seems not to be the case. The evidence we have from various spot checks by EPA and GAO suggests that most industrial polluters seem to be in compliance most of the time.[31] Substantial compliance seems

[30] Russell, Harrington, and William Vaughan (1986, ch. 4) provide a useful survey of the enforcement literature in environmental economics up to 1985. Harrington (1988) presents a concise, excellent overview both of the more recent literature and of the "stylized facts" of actual compliance and enforcement behavior. See also Russell (1990).

[31] Interestingly, noncompliance seems to be more widespread among municipal waste treatment plants than among industrial sources! (Russell 1990, p. 256). Some of the most formidable enforcement problems involve federal agencies. The GAO (1988), for example, has found the Department of Energy's nuclear weapons facilities to be a source of major concern; the costs of dealing with environmental contamination associated with these facilities are estimated at more than $100 billion.

to exist in spite of modest enforcement efforts: relatively few "notices of violation" have been issued and far fewer polluters have actually been fined for their violations. Moreover, where such fines have been levied, they have typically been quite small. And yet in spite of such modest enforcement efforts, "cheating" is not ubiquitous—violations are certainly not infrequent, but they are far from universal.

This finding simply doesn't square at all well with the results from the static models of polluter behavior.[32] An alternative line of modeling (drawing on the tax-evasion literature) seems to provide a better description of polluter behavior; it also has some potentially instructive normative implications. This approach puts the problem in a dynamic game-theoretic framework. Both polluters and regulators react to the activities of one another in the previous period. In a provocative paper, Harrington (1988) models the enforcement process as a Markov decision problem. Polluters that are detected in violation in one period are moved to a separate group in the next period in which they are subject to more frequent inspection and higher fines. Polluting firms thus have an incentive to comply in order to avoid being moved into the second group (from which they can return to the original group only after a period during which no violations are detected). In such a framework, firms may be in compliance even though they would be subject to no fine for a violation. Following up on Russell's analysis (Russell, Harrington, and Vaughan 1986, pp. 199–216), Harrington finds that the addition of yet a third group, an absorbing state from which the polluter can never emerge, can result in a "spectacular reduction in the minimum resources required to achieve a given level of compliance" (p. 47). In sum, the dynamic game-theoretic approach can produce compliance in cases in which the expected penalty is insufficient to prevent violations in a purely static model. Moreover, it suggests some potentially valuable guidelines for the design of cost-effective enforcement procedures. Enforcement is an area where economic analysis may make some quite useful contributions.

G. *The Effects of Domestic Environmental Policy on Patterns of International Trade*

The introduction of policy measures to protect the environment has potential implications not only for the domestic economy but also for international trade. Proposed environmental regulations are, in fact, often opposed vigorously on the grounds that they will impair the "international competitiveness" of domestic industries. The increased costs associated with pollution control measures will, so the argument goes, result in a loss of export markets and increased imports of products of polluting industries.

These potential effects have been the subject of some study. It is clear, for example, that the adoption of costly control measures in certain countries will, in principle, alter the international structure of relative costs with potential effects on patterns of specialization and world trade. These trade effects have been explored in some detail, making use of standard models of international trade (Kazumi Asako 1979; Baumol and Oates 1988, ch. 16; Anthony Koo 1974; Martin McGuire 1982; John Merrifield 1988; Rüdiger Pethig 1976; Pethig et al. 1980; Horst Siebert 1974; James Tobey 1989; Ingo Walter 1975). In particular, there has been a concern that the less developed countries, with their emphasis on

[32] Perhaps public opprobrium is a stronger disciplinary force than economists are typically inclined to believe!

economic development rather than environmental protection, will tend over time to develop a comparative advantage in pollution-intensive industries. In consequence, they will become the "havens" for the world's dirty industries; this concern has become known as the "pollution-haven hypothesis" (Walter and Judith Ugelow 1979; Walter 1982).

Some early studies made use of existing macro-econometric models to assess the likely magnitudes of these effects. These studies used estimates of the costs of pollution control programs on an industry basis to get some sense of the effects of these programs on trade and payments flows. Generally, they found small, but measurable, effects (d'Arge and Kneese 1971; Walter 1974).

We are now in a position to examine historically what has, in fact, happened. To what extent have environmental measures influenced the pattern of world trade? Have the LDC's become the havens of the world's dirty industries? Two recent studies, quite different in character, have addressed this issue directly. H. Jeffrey Leonard (1988), in what is largely a case study of trade and foreign-investment flows for several key industries and countries, finds little evidence that pollution-control measures have exerted a systematic effect on international trade and investment. After examining some aggregate figures, the policy stances in several industrialized and developing countries, and the operations of multinational corporations, Leonard concludes that "the differentials in the costs of complying with environmental regulations and in the levels of environmental concern in industrialized and industrializing countries have not been strong enough to offset larger political and economic forces in shaping aggregate international comparative advantage" (p. 231).

Tobey (1989, 1990) has looked at the same issue in a large econometric study of international trade patterns in "pollution-intensive" goods. After controlling for the effects of relative factor abundance and other trade determinants, Tobey cannot find any effects of various measures of the stringency of domestic environmental policies. Tobey estimates two sets of equations that explain, respectively, patterns of trade in pollution-intensive goods and changes in trade patterns from 1970 to 1984. In neither set of equations do the variables measuring the stringency of domestic environmental policy have the predicted effect on trade patterns.

Why have domestic environmental measures not induced "industrial flight;" and the development of "pollution havens?" The primary reason seems to be that the costs of pollution control have not, in fact, loomed very large even in heavily polluting industries. Existing estimates suggest that control costs have run on the order of only 1 to 2½ percent of total costs in most pollution-intensive industries; H. David Robison (1985, p. 704), for example, reports that total abatement costs per dollar of output in 1977 were well under 3 percent in all industries with the sole exception of electric utilities where they were 5.4 percent. Such small increments to costs are likely to be swamped in their impact on international trade by the much larger effects of changing differentials in labor costs, swings in exchange rates, etc. Moreover, nearly all the industrialized countries have introduced environmental measures—and at roughly the same time—so that such measures have not been the source of significant cost differentials among major competitors. There seems not to have been a discernible movement in investment in these industries to the developing countries because major political and economic uncertainties have apparently loomed much larger in location decisions than have the modest savings from less stringent environmental controls.

In short, domestic environmental policies, at least to this point in time, do not appear to have had significant effects on patterns of international trade. From an environmental perspective, this is a comforting finding, for it means that there is little force to the argument that we need to relax environmental policies to preserve international competitiveness.

H. *Command-and-Control vs. Economic Incentives: Some Concluding Observations*

Much of the literature in environmental economics, both theoretical and empirical, contrasts in quite sharp and uncompromising terms the properties of systems of economic incentives with the inferior outcomes under existing systems of command-and-control regulations. In certain respects, this literature has been a bit misleading and, perhaps, unfair. The term command-and-control encompasses a very broad and diverse set of regulatory techniques—some admittedly quite crude and excessively costly. But others are far more sophisticated and cost sensitive. In fact, the dividing line between so-called CAC and incentive-based policies is not always so clear. A program under which the regulator specifies tho exact treatment procedures to be followed by polluters obviously falls within the CAC class. But what about a policy that establishes a fixed emissions limitation for a particular source (with no trading possible) but allows the polluter to select the form of compliance? Such flexibility certainly allows the operation of economic incentives in terms of the search for the least-cost method of control.

The point here is that it can be quite misleading to lump together in a cavalier fashion "CAC" methods of regulatory control and to contrast them as a class with the least-cost outcomes typically associated with systems of economic incentives. In fact, the compromises and "imperfections" inherent in the design and implementation of incentive-based systems virtually guarantee that they also will be unable to realize the formal least-cost result.

Empirical studies contrasting the cost effectiveness of the two general approaches have typically examined the cost under each system of attaining a specified *standard* of environmental quality—which typically means ensuring that at no point in an area do pollutant concentrations exceed the maximum level permissible under the particular standard. As Atkinson and Tietenberg (1982) and others have noted, CAC systems typically result in substantial "overcontrol" relative to incentive-based systems. Since it effectively assigns a zero shadow price to any environmental improvements over and above the standard, the least-cost algorithm attempts to make use of any "excess" environmental capacity to increase emissions and thereby reduce control costs. The less cost-sensitive CAC approaches generally overly restrict emissions (relative to the least-cost solution) and thereby produce pollutant concentrations at nonbinding points that are less than those under the least-cost outcome. In sum, at most points in the area, environmental quality (although subject to the same overall standard) will be higher under a CAC system than under the least-cost solution. So long as there is some value to improved environmental quality beyond the standard, a proper comparison of benefits and costs should give the CAC system credit for this increment to environmental quality. One recent study (Oates, Paul Portney, and McCartland 1989) which does just this for a major air pollutant finds that a relatively sophisticated CAC approach produces results that compare reasonably well to the prospective outcome under a fully cost effective system of economic incentives.

Our intent is not to suggest that the economist's emphasis on systems of economic incentives has been misplaced, but rather to argue that policy structure and analysis is a good deal more complicated than the usual textbooks would suggest (Nichols 1984). The applicability of systems of economic incentives is to some extent limited by monitoring capabilities and spatial complications. In fact, in any meaningful sense the "optimal" structure of regulatory programs for the control of air and water pollution is going to involve a combination of policy instruments—some making use of economic incentives and others not. Careful economic analysis has, we believe, an important role to play in understanding the workings of these systems. But it can make its best contribution, not through a dogmatic commitment to economic incentives, but rather by the careful analysis of the whole range of policy instruments available, insuring that those CAC measures that are adopted are effective devices for controlling pollution at relatively modest cost (Kolstad 1986).

At the same time, it is our sense that incentive-based systems have much to contribute to environmental protection—and that they have been much neglected in part because of the (understandable) predisposition of regulators to more traditional policy instruments.[33] There are strong reasons for believing, with supporting evidence, that this neglect has seriously impaired our efforts both to realize our objectives for improved environmental quality and to do so at the lowest cost. A general realization of this point seems to be emerging with a consequent renewed interest in many countries in the possibility of integrating incentive-based policies into environmental regulations—a matter to which we shall return in the concluding section.

IV. *Measuring the Benefits and Costs of Pollution Control*

As we suggested in the previous sections, effluent fees and transferable permits are capable, in principle, of achieving a given pollution standard at least cost. Eventually, however, economists must ask whether environmental standards have been set at appropriate levels: does the marginal cost of achieving the ozone standard in the Los Angeles basin exceed the marginal benefits? The answer to this question requires that we measure the benefits and costs of pollution control.

While the measurement of control costs is itself no simple task, environmental economists have turned most of their attention to the benefit side of the ledger. Of central concern has been the development of methodologies to measure the benefits of goods—such as clean air or water—that are not sold in markets. These techniques fall into two categories: indirect market methods, which attempt to infer from actual choices, such as choosing where to live, the value people place on environmental goods; and direct questioning approaches, which ask people to make tradeoffs between environmental and other goods in a survey context. We shall review both approaches, and then discuss the application of these methods to valuing the benefits of pollution control. In particular, we will try to highlight areas where benefits have been successfully measured, as well as areas where good benefit estimates are

[33] See Steven Kelman (1981) for a fascinating—if somewhat dismaying—study of the politics and ideology of economic incentives for environmental protection.

most needed. But first we must be clear about the valuation of changes in environmental quality.

A. *Defining the Value of a Change in Environmental Quality*

We noted at the beginning of this review that pollution may enter both consumers' utility functions and firms' production functions. (See equations (1) and (2).) To elaborate on how this might occur we introduce a *damage function* that links pollution, Q, to something people value, S,

$$S = S(Q). \tag{8}$$

For a consumer, S might be time spent ill or expected fish catch; for a firm it might be an input into production, such as the stock of halibut. We assume that S replaces Q in the utility and production functions (equations (1) and (2)).

There are two cases of interest here. First, if the consumer (or firm) views S as out of his control, we can define the value of a change in S (which may be easier to measure than the value of a change in Q), and then predict the change in S resulting from a change in Q. For example, if people view reductions in visibility associated with air pollution as beyond their control, one can predict the reduction in visibility from (8) and concentrate on valuing visibility. This is commonly known as the damage function approach to benefit estimation.

The second case is more complicated. It may sometimes be possible to mitigate the effects of pollution through the use of inputs, Z. For example, medicine may exist to alleviate respiratory symptoms associated with air pollution. In this instance, equation (8) must be modified to

$$S = S(Q,Z), \tag{9}$$

and it is Q rather than S that must be valued, because S is no longer exogenous.

For the case of a firm, the value of a change in Q (or S) is the change in the firm's profits when Q (or S) is altered. This amount is the same whether we are talking about the firm's willingness to pay (WTP) for an improvement in environmental quality or its willingness to accept (WTA) compensation for a reduction in environmental quality.

For a consumer, in contrast, the value of a change in Q (or S) depends on the initial assignment of property rights. If consumers are viewed as having to pay for an improvement in environmental quality, for example, from Q^0 to Q^1, the most they should be willing to pay for this change is the reduction in expenditure necessary to achieve their original utility level when Q improves. Formally, if $e(P,S(Q^0),U^0)$ denotes the minimum expenditure necessary to achieve pre-improvement utility U^0 at prices P and environmental quality Q^0, then the most people would be willing to pay (WTP) for the improvement in environmental quality to Q^1 is

$$WTP = e(P,S(Q^0),U^0) - e(P,S(Q^1),U^0). \tag{10}$$

If, on the other hand, consumers are viewed as having rights to the higher level of environmental quality and must be compensated for a reduction in Q, then the smallest amount they would be willing to accept is the additional amount they must spend to achieve their original utility level when Q declines. Formally, willingness to accept (WTA) compensation for a reduction in Q from Q^1 to Q^0 is given by

$$WTA = e(P,S(Q^0),U^1) - e(P,S(Q^1),U^1), \tag{11}$$

where U^1 is the utility level achieved at the higher level of environmental quality.

In general, willingness to accept compensation for a reduction in Q will be higher than willingness to pay for an increase in Q of the same magnitude. As W. Michael Hanemann (1991) has recently shown, the amount by which *WTA* exceeds *WTP* varies directly with the income elasticity of demand for S and inversely with the elasticity of substitution between S and private goods. If the income elasticity of demand for S is zero or if S is a perfect substitute for a private good, *WTP* should equal *WTA*. If, however, the elasticity of substitution between S and private goods is zero, the difference between *WTA* and *WTP* can be infinite. It is therefore important to determine which valuation concept, *WTP* or *WTA*, is appropriate for the problem at hand.

The preceding definitions of the value of a change in environmental quality do not by themselves characterize all of the welfare effects of environmental policies. Improvements in environmental quality may alter prices as well as air or water quality, and these price changes must be valued in addition to quality changes.

In contrast to valuing quality changes, valuing price changes is relatively straightforward. *WTP* for a reduction in price is just the reduction in expenditure necessary to achieve U^0 (the consumer's original utility level) when prices are reduced. As is well known, this is just the area to the left of the relevant compensated demand function (i.e., the one that holds utility at U^0) between the two prices. Willingness to accept compensation for a price increase is the increase in expenditure necessary to achieve U^1, the utility level enjoyed at the lower price, when price is increased.

Unlike the case of a quality change, *WTA* compensation for a price increase exceeds *WTP* for a price decrease only by the amount of an income effect. As long as expenditure on the good in question is a small fraction of total expenditure, the difference between the two welfare measures will be small. Moreover, approximating *WTP* or *WTA* by consumer surplus—the area to the left of the Marshallian demand function will produce an error of no more than 5 percent in most cases (Robert Willig 1976).[34]

One problem with the definitions of the value of a change in environmental quality (equations (10) and (11)) is that not all environmental benefits can be viewed as certain. Reducing exposure to a carcinogen, for example, alters the probability that persons in the exposed population will contract cancer, and it is this probability that must be valued.

To define the value of a quality change under uncertainty, suppose that the value of S associated with a given Q is uncertain. Specifically, suppose that two values of S are possible: S^0 and S^1. For example, S^0 might be 360 healthy days per year and S^1 no healthy days (death). Q no longer determines S directly, but affects π, the probability that S^0 occurs. If the individual is an expected utility maximizer and if $V(M,S^i)$, $i = 0,1$, denotes his expected utility in each state (M being income), willingness to pay for a change in Q from Q^0 to Q^1 is the most one can take away from the individual and leave him at his original expected utility level (Michael Jones-Lee 1974).

$$\pi(Q^0)V(M,S^0) + [1-\pi(Q^0)]V(M,S^1) = \pi(Q^1)V(M-WTP,S^0) + [1-\pi(Q^1)]V(M-WTP,S^1). \tag{12}$$

For a small change in Q, *WTP* is just the difference in utility between the two states, divided by the expected marginal utility of money,

[34] Sufficient conditions for this to hold are that (1) consumer surplus is no more than 90 percent of income; (2) the ratio of consumer surplus to income, multiplied by one-half the income elasticity of demand, is no more than 0.05.

$$WTP = \frac{[V(M,S^0) - V(M,S^1)]}{\pi V_M^0 + (1-\pi)V_M^1} \cdot \frac{\partial \pi}{\partial Q} dQ. \quad (13)$$

An important point to note here is that the value of the change in Q is an ex ante value: changes in Q are valued before the outcomes are known. For example, suppose that reducing exposure to an environmental carcinogen is expected to save two lives in a city of 1,000,000 persons. The ex ante approach views this as a 2-in-one-million reduction in the probability of death for each person in the population. The ex post approach, by contrast, would value the reduction in two lives with certainty.

We are now in a position to discuss the principal methods that have been used to value changes in pollution.

B. *Indirect Methods for Measuring the Benefits of Environmental Quality*

Economists have employed three approaches to valuing pollution that rely on observed choices: the averting behavior approach, the weak complementarity approach, and the hedonic price approach.

1. *The Averting Behavior Approach.* The averting behavior approach relies on the fact that in some cases purchased inputs can be used to mitigate the effects of pollution.[35] For example, farmers can increase the amount of land and other inputs to compensate for the fact that ozone reduces soybean yields. Or, for another, residents of smoggy areas can take medicine to relieve itchy eyes and runny noses.

As long as other inputs can be used to compensate for the effects of pollution, the value of a small change in pollution can be measured by the value of the inputs used to compensate for the change in pollution. If, for example, a reduction in one-hour maximum ozone levels from 0.16 parts per million (ppm) to 0.11 ppm reduces the number of days of respiratory symptoms from 6 to 5, and if an expenditure on medication of $20 has the same effect, then the value of the ozone reduction is $20.

Somewhat more formally, if $S = S(Q,Z)$, willingness to pay for a marginal change in Q may be written as the marginal rate of substitution between an averting good and pollution, times the price of the averting good (Paul Courant and Richard Porter 1981).

$$WTP = -p_1 \frac{\partial S/\partial Q}{\partial S/\partial z_1}, \quad (14)$$

where z_1 is medication. Marginal WTP can thus be estimated from the production function alone.

To value a nonmarginal change in pollution, one must know both the cost function for the good affected by pollution and the marginal value function for that good. For example, in the case of health damages, a large improvement in air quality will shift the marginal cost of healthy days to the right (see Figure 1) and the value of the change is given by the area between the two marginal cost curves, bounded by the marginal value of healthy time. When the good in question is not sold in markets, as is the case for health, estimating the marginal value function is, however, difficult.[36]

[35] In terms of the notation above, either (9) applies, or other inputs can be substituted for S in production; see equation (2).

[36] If S were sold in markets, estimation of the marginal value function would be simple, assuming one could observe the price of S and assuming that the price was exogenous to any household. The problem is that, for a good produced by the household itself, one cannot observe the price (marginal cost) of the good—it must be estimated from the marginal cost function. Furthermore, the price is endogenous, since it depends on the level of S.

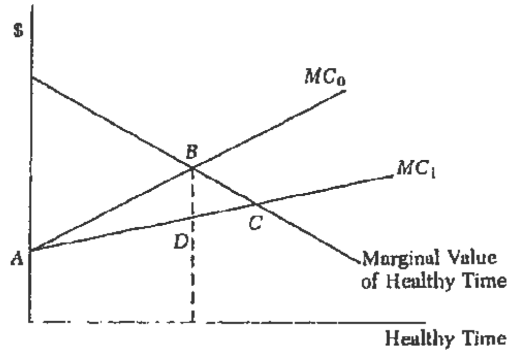

Figure 1. Morbidity Benefits of a Nonmarginal Pollution Reduction

An alternative approach, suggested by Bartik (1988a), is to use the change in the cost of producing the original level of S, i.e., the area between the marginal cost functions to the left of S^0 (area ABD in Figure 1), to approximate the value of the environmental quality change. For an improvement in Q, this understates the value of the change because it does not allow the individual to increase his chosen value of S. When the marginal cost of S increases, the relevant area will overstate the value of the welfare decrease. The advantage of this approximation is that it can be estimated from knowledge of the cost function alone.

The usefulness of the averting behavior approach is clearly limited to cases where other inputs can be substituted for pollution. Most pollution damages suffered by firms occur in agriculture, forestry, and fishing. In the case of agriculture, irrigation can compensate for the effects of global warming on crop yields. Likewise, capital (boats and gear) and labor can compensate for fish populations depleted as a result of water pollution.

In the case of pollution damages suffered by households, averting behavior has been used to value health damages and the soiling damages caused by air pollution. Households can avoid health damages either by avoiding exposure to pollution in the first place, or by mitigating the effects of exposure once they occur. For example, the deleterious effects of water pollution can be avoided by purchasing bottled water (V. Kerry Smith and William Desvousges 1986b), and pollutants in outdoor air may be filtered by running an air-conditioner (Mark Dickie and Shelby Gerking 1991).

Two problems, however, arise in applying the averting behavior method in these cases. First, in computing the right-hand-side of (14), the researcher must know what the household imagined the benefit of purchasing water ($\partial S/\partial z_1$) to be, since it is the *perceived* benefits of averting behavior that the household equates to the marginal cost of this behavior. Second, when the averting input produces joint products, as in the case of running an air-conditioner, the cost of the activity cannot be attributed solely to averting behavior. Inputs that mitigate the effects of pollution include medicine and doctors' visits (Gerking and Linda Stanley 1986); however, use of the latter often runs into the joint product problem—a doctor's visit may treat ailments unrelated to pollution, as well as pollution related illness.

2. *The Weak Complementarity Approach.* While the averting behavior approach exploits the substitutability between pollution and other inputs into production, the weak complementarity approach values changes in environmental quality by making use of the complementarity of environmental quality, e.g., cleaner water, with a purchased good, e.g., visits to a lake. Suppose that a specified improvement in water quality at a lake resort results in an increase in a household's demand for visits to the resort from ED to AB (see Figure 2). One can view the value of access to the lake at the original quality level Q^0 as the value of being able to visit the lake at a cost of C rather than at some cost E.

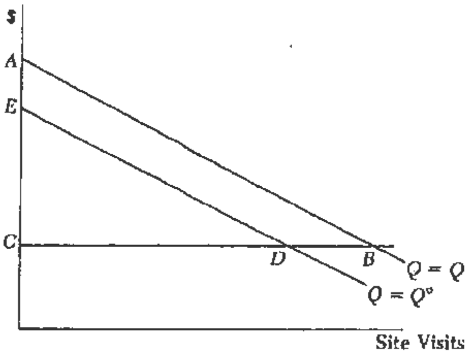

Figure 2. The Effect of a Change in Environmental Quality on the Demand for Visits to a Recreation Site

The value of access to the lake is thus the area *EDC*.[37] The increase in the value of access when *Q* changes (area *ABDE*) is the value of the water quality improvement.

For area ABDE to measure the value of the water quality improvement, environmental quality must be weakly complementary to the good in question (Mäler 1974; Nancy Bockstael and Kenneth McConnell 1983). This means that (1) the marginal utility of environmental quality (water quality) must be zero if none of the good is purchased (no visits are made to the lake); (2) there is a price above which none of the good is purchased (no visits are made). If (1) did not hold, three would he additional benefits to a change in water quality not reflected in the demand for visits.

In practice, the weak complementarity approach has been used most often to value the attributes of recreation sites—either water quality, or a related attribute, such as fish catch.[38] Although site visits do not have a market price, their cost can be measured by summing the cost of traveling to the site, including the time cost, as well as any entrance fees.

A problem in measuring the demand for site visits as a function of site quality is that there is no variation in site quality among persons who visit a site. A popular solution to this problem is the varying parameters model, which assumes that site quality enters recreation demand functions multiplied by travel cost or income, both of which vary across households.[39] In the first stage of the model, the demand for visits to site *i* is regressed on the cost of visiting the site and on income. In the second stage the coefficients from stage one are regressed on quality variables at site *i*. This is equivalent to estimating a set of demand functions in which visits to site *i* depend on the quality of the *i*th site, the cost of visiting the *i*th site, income, and interactions between travel cost and quality, and income and quality.

One drawback of this approach is that it allows visits to a given site to depend only on the cost of visiting that site—the cost of visiting substitute sites is not considered. This is equivalent to assuming that, except for the quality variables that enter the model in stage two, all sites are perfect substitutes. The varying parameters model may, therefore, give misleading results if one wishes to value quality changes at several sites.

A second approach to valuing quality changes is to use a discrete choice model. This approach examines the choice of

[37] Strictly speaking *EDC* should be measured using the consumer's compensated demand function. When measuring the value of access to a good, use of the Marshallian demand function may no longer provide a good approximation to the welfare triangle since the choke prices of the Marshallian and compensated demand functions may vary substantially. The Willig bounds do not apply in this case.

[38] Surveys of recreation demand models may be found in Mendelsohn (1987) and also in John Braden and Kolstad (1991). Bockstael, Hanemann, and Catherine Kling (1987) discuss their application to valuing environmental quality at recreation sites.

[39] This solution was first used by Vaughan and Russell (1982) and has also been used by V. Kerry Smith, Desvousges, and Matthew McGivney (1983), and V. Kerry Smith and Desvousges (1986a).

which site to visit on a given day as a function of the cost of visiting each site, and the quality of each site. If the choice of which site to visit on the first recreation day can be viewed as independent of which site to visit on the ith, a simple discrete choice model, such as the multinomial logit, can be applied to the choice of site, conditional on participation (Clark Binkley and Hanemann 1978; Daniel Feenberg and Mills 1980). The choice of whether to participate and, if so, on how many days, is made by comparing the maximum utility received from taking a trip with the utility of the best substitute activity on that day.[40]

The advantage of the discrete choice model is that the probability of visiting any one site depends on the costs of visiting all sites and the levels of quality at all sites. The drawback of the model is that the decision to take a trip or not and, if so, which site to visit, is made independently on each day of the season. The number of trips made to date influence neither which site the individual chooses to go to on a given day, nor whether he takes a trip at all.[41] Thus, these models must be combined with models that predict the total number of trips taken.

3. *Hedonic Market Methods.* The third method used by economists to value environmental quality, or a related output such as mortality risk, exploits the concept of hedonic prices—the notion that the price of a house or job can be decomposed into the prices of the attributes that make up the good, such as air quality in the case of a house (Ronald Ridker and John Henning 1967), or risk of death in the case of a job (Richard Thaler and Sherwin Rosen 1976). The hedonic price approach has been used primarily to value environmental disamenities in urban areas (air pollution, proximity to hazardous waste sites), which are reflected both in housing prices and in wages. It has also been used to value mortality risks by examining the compensation workers receive for voluntarily assuming job risks. Finally, the hedonic travel cost approach has been used to value recreation sites. We discuss each approach in turn.

Urban Amenities. Air quality and other environmental amenities can be valued in an urban setting by virtue of being tied to residential location: they are part of the bundle of amenities—public schools, police protection, proximity to parks—that a household purchases when buying a house.

The essence of the hedonic approach is to try to decompose the price of a house (or of residential land) into the prices of individual attributes, including air quality. This is done using an hedonic price function, which describes the equilibrium relationship between house price, p, and attributes, $A = (a_1, a_2, \ldots, a_n)$. The marginal price of an attribute in the market is simply the partial derivative of the hedonic price function with respect to that attribute. In selecting a house, consumers equate their marginal willingness to pay for each attribute to its marginal price (S. Rosen 1974; A. Myrick Freeman 1974). This implies that

[40] If one estimates a discrete choice model of recreation decisions, the value of a change in environmental quality at site i is no longer measured as indicated in Figure 2 (Hanemann 1984). Because utility is random from the viewpoint of the researcher, compensating variation for a change in quality at a recreation site on a given day equals the change in utility conditional on visiting the site times the probability that the site is visited, plus the change in the probability of visiting the site times the utility received from the site.

[41] One solution to this problem, proposed by Edward Morey (1984), is to estimate a share model, which allocates the recreation budget for a season among different sites. The drawback of this model is that the share of the budget going to each site is assumed to be positive, whereas, in reality, a household may not visit all sites.

the gradient of the hedonic price function, evaluated at the chosen house, gives the buyer's marginal willingnesses to pay for each attribute.

Somewhat more formally, utility maximization in an hedonic market calls for the marginal price of an attribute to equal the household's marginal willingness to pay for the attribute,

$$\partial p/\partial a_i = \partial\theta/\partial a_i, \qquad (15)$$

where θ is the household's bid function, the most one can take away from the household in return for the collection of amenities, A, and keep its utility constant. Equation (15) implies that, in equilibrium, the marginal willingness to pay for an attribute can be measured by its marginal price, computed from the hedonic price function.

If a large improvement in environmental quality is contemplated in one section of a city—an improvement large enough to alter housing prices—the derivative of the hedonic price function no longer measures the value of the amenity change. In the short run, before households adjust to the amenity change and prices are altered, the value of the amenity change is the area under the household's marginal bid function—the right hand side of (15)—between the old and new levels of air quality. To value the amenity change in the long run, however, one must take into account the household's adjustment to the amenity change *and* to any price changes that may result. The area under the marginal bid function (the short-run welfare measure) is, however, a lower bound to the long-run benefits of the amenity change (Bartik 1988b).

Empirical applications of the hedonic approach have typically focused either on valuing marginal amenity changes, which requires estimating only the hedonic price function, or on computing the short-run benefits of nonmarginal amenity changes, which requires estimating marginal bid functions. S. Rosen originally suggested that this be done by regressing marginal attribute price, computed from the gradient of the hedonic price function, on the arguments of the marginal bid function. This procedure, however, may encounter an identification problem which is caused by the fact that the arguments of the marginal attribute bid function determine marginal attribute price as well.

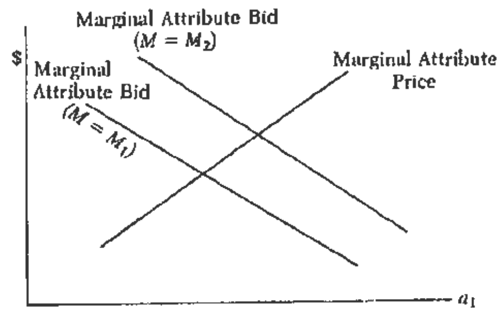

Figure 3. The Identification Problem in an Hedonic Market

An example of the identification problem, provided by James Brown and Harvey Rosen (1982), occurs when the hedonic price function is quadratic and the marginal value functions are linear in attributes. In the case of a single amenity, a_1,

$$\partial p/\partial a_1 = \beta_0 + \beta_1 a_1 \qquad (16)$$

$$\partial\theta/\partial a_1 = b_0 + b_1 a_1 + b_2 M. \qquad (17)$$

In this case regressing $\beta_0 + \beta_1 a_1$ on a_1 and M will reproduce the parameters of the marginal price function, i.e., $\hat{b}_0 = \beta_0$, $\hat{b}_1 = \beta_1$ and $\hat{b}_2 = 0$. This is illustrated graphically in Figure 3. The problem is that the marginal price function does not shift independently of the marginal bid function. Shifts in the latter, due, say, to differences in income, thus trace out points on the marginal price function.

To achieve identification in this example, one can introduce functional form restrictions, such as adding a_1^2 to the marginal price function, but not to the marginal value function, which will cause $\partial p/\partial a_i$ to shift independently of $\partial\theta/\partial a_i$ (Mendelsohn 1984). Another solution is to estimate hedonic price functions for several markets, so that the coefficients of the marginal price function vary across cities (Palmquist 1984; Robert Ohsfeldt and Barton Smith 1985; Ohsfeldt 1988). For this to work, households in all cities must have identical preferences; however, the distribution of measured household characteristics and/or the supply of amenities must vary across cities so that the hedonic price function and its gradient vary from one city to another. In the case of several a_i's, one can impose exclusion restrictions on the a_i's that enter each marginal value function (Dennis Epple 1987) so that marginal prices vary independently of the variables that enter the marginal value function.

In view of the problems in estimating marginal attribute bid functions, it is important to note that an upper bound to the long-run benefits of an amenity improvement can be obtained from the hedonic price function alone. Yoshitsugu Kanemoto (1988) has shown that the change in prices in the improved area predicted by the hedonic price function is an upper bound to the long-run benefits of an amenity improvement. Thus, from knowledge of the hedonic price function alone one can obtain (1) the exact value of a marginal attribute change, and (2) an upper bound to the long-run value of an attribute change.

Wage-Amenity Studies. The analysis of hedonic housing markets, by focusing on housing market equilibrium within a city, implicitly ignores migration among cities. If one takes a long-run view and assumes that workers can move freely from one city to another, then data on compensating wage differentials across cities can be used to infer the value of environmental amenities (Glenn Blomquist, Mark Berger, and John Hoehn 1988; Maureen Cropper and Amalia Arriaga-Salinas 1980; V. Kerry Smith 1983). Intuitively, the value people attach to urban amenities should be reflected in the higher wages they require to live in less desirable cities.

When migration is possible, consumers choose the city in which they live to maximize utility; however, wage income, as well as amenities, vary from one city to another (S. Rosen 1979; Jennifer Roback 1982).[42] Household equilibrium requires that utility be identical in all cities.

The fact that consumers in all cities must enjoy the same level of utility implies that wages and land rents must adjust to compensate for amenity differences. The marginal value of an amenity change to a consumer is thus the sum of the partial derivatives of an hedonic wage function and an hedonic property value function (Roback 1982).

Hedonic Labor Markets. The fact that risk of death is a job attribute traded in hedonic labor markets has provided economists with an alternative to the averting behavior approach as a means of valuing mortality risk (Thaler and S. Rosen 1976). The theory behind this approach is simple: other things equal, workers in riskier jobs must be compensated with higher wages for bearing this risk. As in the case of hedonic housing markets, the worker chooses his job by equating the marginal cost of working in a less risky job—the derivative of the hedonic price function—to the marginal benefit, the value (in dollars) of the resulting increase in life expectancy.

There are three problems in using the compensating wage approach. One is

[42] In most models wages, lot size, and amenities vary among, but not within, cities.

that compensating wage differentials exist only if workers are informed of job risks. Thus, the absence of compensating differentials need not mean that workers do not value reducing the risk of death. A second problem is that compensating differentials appear to exist only in unionized industries (William Dickens 1984; Douglas Gegax, Gerking, and Schulze 1985). This suggests that the wage differential approach may provide estimates of the value of a risk reduction only for certain segments of the population. This problem is compounded by the fact that the least risk averse individuals work in risky jobs. Third, if workers have biased estimates of job risks, or if the objective measures of job risk used in most wage studies over- or understate workers' risk perceptions, market wage premia will yield biased estimates of the value of a risk reduction.

The Hedonic Travel Cost Approach. Yet another area in which the hedonic approach has been applied is in valuing the attributes of recreation sites (G. Brown and Mendelsohn 1984). In valuing sites, the analog to the hedonic price function is obtained by regressing the cost of travelling to a recreation site on the attributes of the site, such as expected fish catch, clarity of water, and water color. However, because this relationship is not the result of market forces, there is nothing to guarantee that the marginal cost of an attribute is positive. More desirable sites may be located closer to population centers rather than farther away from them.[43] In this case, the individual's choice of site will not be described by (13), and care must be taken when inferring values from marginal attribute costs (V. Kerry Smith, Palmquist, and Paul Jakus 1990).

[43] The problem may be reduced by using only sites actually visited from a given origin in estimating the hedonic travel cost function.

C. *The Contingent Valuation Method*

While the indirect market approaches we have described above can be used to value many of the benefits of pollution reduction, there are important cases in which they cannot be used. When no appropriate averting or mitigating behavior exists, indirect methods cannot be used to estimate the morbidity benefits of reducing air pollution. Recreation benefits may be difficult to measure since there may not be enough variation in environmental quality across sites in a region to estimate the value of water quality using the travel cost approach.

There is, in addition, an entire category of benefits—*nonuse values*—which cannot even in principle be measured by indirect market methods. Nonuse values refer to the benefits received from knowing that a good exists, even though the individual may never experience the good directly. Examples include preserving an endangered species or improving visibility at the Grand Canyon for persons who never plan to visit the Grand Canyon.

This suggests that direct questioning can play a role in valuing the benefits of pollution control. Typically, direct questioning or contingent valuation studies ask respondents to value an output, such as a day spent hunting or fishing, rather than a change in pollution concentrations per se. Examples of commodities that have been valued using the contingent valuation method (CVM) include improvements in water quality to the point where the water is fishable or swimmable (Richard Carson and Robert Mitchell 1988), improvements in visibility resulting from decreased air pollution (Alan Randall, Berry Ives, and Clyde Eastman 1974; Schulze and David Brookshire 1983; Decision Focus 1990), the value of preserving endangered species (James Bowker and John Stoll 1988;

Kevin Boyle and Richard Bishop 1987), and days free of respiratory symptoms (George Tolley et al. 1986b; Dickie et al. 1987).

Any contingent valuation study must incorporate (1) a description of the commodity to be valued; (2) a method by which payment is to be made; and (3) a method of eliciting values. In studies that value recreation-related goods, hypothetical payment may take the form of a user fee or an increase in taxes; in the case of improved visibility, a charge on one's utility bill, since power plant pollution can contribute to air quality degradation. To determine the maximum a person is willing to pay for an improvement in environmental quality, the interviewer may simply ask what this amount is (an open-ended survey), or he may ask whether or not the respondent is willing to pay a stated amount (a closed-ended survey). The yes/no answer does not yield an estimate of each respondent's willingness to pay; however, the fraction of respondents willing to pay at least the stated amount gives a point on the cumulative distribution function of willingness to pay for the commodity (Trudy Cameron and Michelle James 1987).

There seems to be general agreement that closed-ended questions are easier for respondents to answer and therefore yield more reliable information than open-ended questions, especially when the commodity valued is not traded in conventional markets. Asking an open-ended question about a good that respondents have never been asked to value, such as improved visibility, often yields a distribution of responses that has a large number of zero values and a few very large ones. This may reflect the fact that respondents have nothing to which to anchor their responses, and are unwilling to go through the reasoning necessary to discover the value they place on the good. Answering a yes/no question is, by contrast, a much easier task, and one that parallels decisions made when purchasing goods sold in conventional markets.

It must be acknowledged that, despite advances made in contingent valuation methodology during the last 15 years, many remain skeptical of the method. Perhaps the most serious criticism is that responses to contingent valuation questions are hypothetical—they represent professed, rather than actual, willingness to pay. This issue has been investigated in at least a dozen studies that compare responses to contingent valuation questions with actual payments for the same commodity.

How close hypothetical values are to actual ones depends on whether the commodity is a public or private good, on the elicitation technique used, and on whether it is willingness to pay (*WTP*) for the good or willingness to accept compensation (*WTA*) that is elicited. Most experiments comparing hypothetical and actual *WTP* for a private good (strawberries or hunting permits) have found no statistically significant difference between mean values of hypothetical and actual willingness to pay (Dickie, Ann Fisher, and Gerking 1987; Bishop and Thomas Heberlein 1979; Bishop, Heberlein, and Mary Jo Kealy 1983). Such is not the case when hypothetical and actual *WTA* are compared. In three experiments involving willingness to accept compensation for hunting permits, Bishop and Heberlein (1979) and Bishop, Heberlein, and Kealy (1983) found that actual *WTA* was statistically significantly lower than hypothetical WTA in two out of three cases. Hypothetical and actual *WTP* have also been found to differ when the commodity valued is a public good (Kealy, Jack Dovidio, and Mark L. Rockel 1987).

Other criticisms of the CVM have focused on: (1) the possibility that individuals may behave strategically in answering questions—either overstating *WTP* if this increases the likelihood that an improvement is made, or understating *WTP* if it reduces their share of the cost (the free-rider problem); (2) the fact that individuals may not be sufficiently familiar with the commodity to have a well-defined value for it; and (3) the fact that *WTP* for a commodity is often an order of magnitude less than willingness to accept (*WTA*) compensation for the loss of the commodity.

The possibility that respondents behave strategically has been tested in laboratory experiments by examining whether announced *WTP* for a public good varies with the method used to finance the public good. Studies by Bohm (1972), Bruce Scherr and Emerson Babb (1975), and Vernon Smith (1977, 1979) suggest that strategic behavior is not a problem, possibly because of the effort that effective strategic behavior requires.

If the commodity to be valued is not well understood, contingent valuation responses are likely to be unreliable: responses tend to exhibit wide variation, and respondents may even prefer less of a good to more! One interpretation of this result is that people really do not have values for the commodity in question—they are created by the researcher in the course of the survey (Thomas Brown and Paul Slovic 1988). This is a serious criticism: Do people really know enough about groundwater contamination or biodiversity to place a value on either good?

Fortunately, it is possible to defend against this criticism by seeing how responses vary with the amount of information that is provided about the commodity being valued. If values are well defined, they should not, on average, vary with small changes in the amount of information.

One of the most striking and challenging findings emerging from this work is that willingness to pay for an environmental improvement is usually *many times lower* than willingness to accept compensation to forego the same improvement (Judd Hammack and G. Brown 1974; Bishop and Heberlein 1979; Robert Rowe, d'Arge, and Brookshire 1980; Jack Knetsch and J. A. Sinden 1984). This is sometimes interpreted as evidence that the method of eliciting responses is unsatisfactory; however, as we noted above, there is no reason why *WTA* for a quality (public good) decrease should not exceed *WTP* for an increase of the same magnitude, provided that there are few substitutes for the public good.[44] An alternative explanation for the *WTA/WTP* discrepancy that has been offered by some economists (Donald Coursey, John Hovis, and Schulze 1987; Brookshire and Coursey 1987) is that individuals are simply not as familiar with the sale of an item as with its purchase. These authors find that, in experiments where individuals were allowed to submit bids or offers for the same commodity, *WTA* approached *WTP* after several rounds of transactions.[45]

D. *Applications of Valuation Techniques*

Having described the main techniques used to value environmental amenities, we now wish to give the reader a feel for the way in which these

[44] The explanation of the discrepancy between *WTA* and *WTP* offered by psychologists—that monetary losses from some reference point are valued more highly than monetary gains (Daniel Kahneman and Amos Tversky 1979)—also suggests that this disparity has nothing to do with flaws in the contingent valuation method.

[45] None of these explanations, however, seems to account for results obtained by Kahneman, Knetsch, and Thaler (1990). They find that, even for common items such as coffee mugs and ballpoint pens, sellers have reservation prices that are higher, much higher on average, than buyers' bid prices. This disparity does not disappear after several rounds of trading. The initial distribution of property rights (the "endowment effect") may, therefore, matter, even for goods with many substitutes.

TABLE 1
TOTAL ANNUALIZED ENVIRONMENTAL COMPLIANCE COSTS, BY MEDIUM, 1990
(Millions of 1986 dollars)

Medium	Costs	Major Statutes
Air and Radiation, Total	28,029	
Air	27,588	Clean Air Act (CAA)
Radiation	441	Radon Pollution Control Act
Water, Total	42,410	
Water Quality	38,823	Clean Water Act (CWA)
Drinking Water	3,587	Safe Drinking Water Act
Land, Total	26,547	
RCRA	24,842	Resource Conservation and Recovery Act (RCRA)
Superfund	1,704	Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)
Chemicals, Total	1,579	
Toxic Substances	600	Toxic Substances Control Act (TSCA)
Pesticides	979	Federal Insecticide, Fungicide and Rodenticide Act (FIFRA)
Total Costs	100,167	

Note: These represent the costs of complying with all federal pollution control laws, assuming full implementation of the law (USEPA 1990).

techniques have been used to value the benefits of pollution control. We shall begin with an overview of the types of benefits associated with the major pieces of environmental legislation. We then turn to a description and assessment of actual benefit estimation.

Table 1 lists the major pieces of environmental legislation in the U.S. and the estimated costs of complying with each statute in 1990. With the exception of the Clean Water Act, the primary goal of U.S. environmental legislation is to protect the health of the population. According to the Clean Air Act, ambient standards for the criteria air pollutants are to be set to protect the health of the most sensitive persons in the population.[46] The goal of the Safe Drinking Water Act is, similarly, to provide a margin of safety in protecting the country's drinking water supplies from toxic substances, while the goal of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) is to prevent adverse effects to human health and to the environment from the use of pesticides.

Each of the statutes in Table 1 also results in certain nonhealth benefits. The Clean Air Act provides important aesthetic benefits in the form of increased visibility, and the 1990 Amendments to the Act, designed to reduce acid rain, may yield ecological and water quality benefits. The Clean Water Act—whose goal is to make all navigable water bodies fishable and swimmable—yields recreational and ecological benefits. Both Acts yield benefits to firms in agriculture, forestry, and commercial fishing. FIFRA, the primary law governing pesticide us-

[46] The criteria air pollutants are particulate matter, sulfur oxides, nitrogen oxides, carbon monoxide, lead, and ozone.

age, is designed to protect animal as well as human health.

In addition to the pollution problem addressed by the major environmental statutes, there is increasing concern about the effects of emissions of greenhouse gases, including carbon dioxide, chlorofluorocarbons (CFCs) and methane. Studies suggest that emissions of these gases may contribute to increases in mean temperature, especially in the Northern Hemisphere, changes in precipitation, and sea level rises that could average 65 cm by the end of the next century. The main effects of these changes are likely to be felt in agriculture, in animal habitat, and in human comfort.

In light of the preceding discussion, we review empirical work for four categories of nonmarket benefits: health, recreation, visibility, and ecological benefits. We also discuss the benefits of pollution control to agriculture.

1. *The Health Benefits of Pollution Control.* The statutes listed in Table 1 contribute to improved human health in several ways. By reducing exposure to carcinogens—in the air, in drinking water, and in food—environmental legislation reduces the probability of death at the end of a latency period—the time that it takes for cancerous cells to develop. Mortality benefits are also associated with control of noncarcinogenic air pollutants, which reduces mortality especially among sensitive persons in the population, e.g., angina sufferers or persons with chronic obstructive lung disease. Lessening children's exposure to lead in gasoline or drinking water avoids learning disabilities and other neurological problems associated with lead poisoning. Finally, controlling air pollution reduces illness—ranging from minor respiratory symptoms associated with smog (runny nose, itchy eyes) to more serious respiratory infections, such as pneumonia and influenza. Water borne disease (e.g., giardiasis) may also cause acute illness.

Reductions in risk of death have been valued using three methods: averting behavior, hedonic analysis, and contingent valuation. The most common approach to valuing changes in risk of death due to environmental causes is hedonic wage studies. The results of these studies are typically expressed in terms of the value per "statistical life" saved. If reducing exposure to some substance reduces current probability of death by 10^{-5} for each of 200,000 persons in a population, it will save two statistical lives ($10^{-5} \times 200{,}000$). If each person is willing to pay $20 for the 10^{-5} risk reduction, then the value of a statistical life is the sum of these willingnesses to pay ($\$20 \times 200{,}000$), divided by the number of statistical lives saved, or $2,000,000.

Recent compensating wage studies (Ann Fisher, Daniel Violette, and Lauraine Chestnut 1989) generate mean estimates of the value of a statistical life that fall within an order of magnitude of one another: $1.6 million to $9 million ($1986), with most studies yielding mean estimates between $1.6 million and $4.0 million. Contingent valuation studies that value reductions in job-related risk of death (Gerking, Menno DeHaan, and Schulze 1988) or reductions in risk of auto death (Jones-Lee, M. Hammerton, and P. R. Philips 1985) fall in the same range.

Averting behavior studies—based on seat belt use (Blomquist 1979) or the use of smoke detectors (Rachel Dardis 1980)—yield estimates of the value of a statistical life that are an order of magnitude lower than the studies cited above. These studies, however, estimate the value of a risk reduction for the person who just finds it worthwhile to undertake the averting activity. This is because buckling a seat belt or purchasing a smoke detector are 0-1 activities. They are undertaken provided that their marginal benefit equals *or exceeds* their marginal cost, with equality of marginal benefit and marginal cost holding only for the marginal purchaser. If 80 percent of all persons use smoke detectors, the value of the risk reduction to the marginal purchaser may be considerably lower than the mean value.

There are, however, other problems in using the indirect market approaches we have reviewed here to value changes in environmental risks. One problem is that the risks valued in labor market and averting behavior studies are more voluntary than many environmental risks. Work by Slovic, Baruch Fischhoff, and Sarah Lichtenstein (1980, 1982) suggests that willingness to pay estimates obtained in one context may not be transferable to the other. Second, death due to an industrial accident is often instantaneous, whereas death resulting from environmental contaminants may come from cancer and involve a long latency period. Deaths due to cancer thus occur in the future and cause fewer years of life to be lost than deaths in industrial accidents. At the same time, however, cancer is one of the most feared causes of death.

In a study designed to value reductions in chemical contaminants (trihalomethanes) in drinking water, Mitchell and Carson (1986) found that the former effect seems to be important: the value of a statistical life associated with a reduction in risk of death 30 years hence was only $181,000 ($1986). This is lower than the value of a statistical life associated with current risk of death for two reasons: (1) the number of expected life years lost is smaller if the risk occurs 20 years hence, and (2) the individual may discount the value of future life years lost (Cropper and Frances Sussman 1990; Cropper and Paul Portney 1990).

In spite of these difficulties, valuing mortality risks is an area in which economists have made important contributions. The notion that, ex ante, individuals are willing to spend only a certain amount to reduce risks to life makes possible rational debate and analysis in the policy arena over tradeoffs in risk reduction. Moreover, estimates of the value of a statistical life are in sufficiently close agreement to permit their use in actual benefit-cost calculations (subject, perhaps, to some sensitivity analysis).

The valuation of morbidity has been less successful. Estimates of the value of reductions in respiratory symptoms come from two sources: averting behavior studies and contingent valuation studies. The averting behavior approach has been used to value illnesses associated with both water and air pollution. It has been more successful in the case of water pollution because an averting behavior exists (buying bottled water) that is closely linked to water pollution (Abdalla 1990; Harrington, Krupnick, and Walter Spofford 1989). By contrast, the averting behaviors used to value air pollution—running an air-conditioner in one's home or car—are in most cases not undertaken primarily because of pollution. The use of doctor visits (purpose unspecified) to mitigate the effects of air pollution suffers from a similar shortcoming.

Contingent valuation studies of respiratory symptoms (coughing, wheezing, sinus congestion) have encountered two problems. The first concerns what is to be valued. Ideally, one would like to value a change in air pollution which, after defensive behavior is undertaken, might cause a change in the level of the symptom experienced. The individual's willingness to pay for the pollution change includes the value of the change in illness after mitigating behavior is undertaken, plus the cost of the mitigating behavior. This suggests that a symptom day be valued after mitigating actions have been taken. A second problem is that the respondent must be encouraged to consider carefully his budget constraint. Failure to handle these problems has led to unbelievably high average values of a symptom day. In more careful studies, mean willingness to pay to eliminate one day of coughing range from $1.39 ($1984) (Dickie et al. 1987) to $42.00 ($1984) (Edna Loehmann et al. 1979); for a day of sinus congestion $1.88 (Dickie et al.) to $52.00 (Loehmann et al.).

An alternative approach to valuing morbidity is to use the cost of illness—the cost of medical treatment plus lost earnings—which, as Harrington and Portney (1976) have shown, is a lower bound to willingness to pay for the change in illness. Mean willingness to pay for symptom reduction is usually three to four times higher than the traditional cost of illness. Berger et al. (1987) report a mean *WTP* of $27 to eliminate a day of sinus congestion, compared with an averge cost of illness of $7. The corresponding figures for throat congestion are $44 and $14.

Studies of willingness to pay to reduce the risk of chronic disease are few (W. Kip Viscusi, Magat, and Joel Huber 1988, is a notable exception), and cost of illness estimates are more prevalent in valuing chronic illness (Ann Bartel and Paul Taubman 1979; Barbara Cooper and Dorothy Rice 1976). Viscusi, Magat, and Huber estimate the value of a statistical case of chronic bronchitis to be $883,000, approximately one-third of the value of a statistical life. This may be contrasted with cost of illness estimates of $200,000 per case of chronic lung disease (Cropper and Krupnick 1989).

As the preceding discussion indicates, more work is needed in the area of both morbidity and mortality valuation. Because of the difficulty in finding activities that mitigate the effects of air pollution, contingent valuation studies would seem to be a more promising approach to valuing morbidity. If new studies are done, they should value combinations of symptoms rather than individual symptoms, since pollution exposures often trigger multiple symptoms, and since the value of jointly reducing several symptoms is generally less than the sum of the values of individual symptom reductions. In the case of mortality risks, more refined estimates are needed that take into account the timing of the risk, the degree of voluntariness, and the cause of death. The timing issue is especially crucial here: the benefits of environmental programs to reduce exposure to carcinogens, such as asbestos, are not realized until the end of a latency period—perhaps 40 years in the case of asbestos. Since the exposed population is 40 years older, fewer life-years are saved, compared with programs that save lives immediately.[47]

2. *The Recreation Benefits of Pollution Control.* Reductions in water pollution may enhance the quality of recreation experiences by allowing (or improving) swimming, boating, or fishing. Most studies of the recreation benefits of water pollution control have focused on fishing-related benefits, and it is on them that we concentrate our attention.

Travel cost studies have taken one of three approaches to valuing the fishing benefits of improved water quality. In some studies (V. Kerry Smith and Desvousges 1986a), measures of water quality such as dissolved oxygen are valued directly. That is, water quality variables directly enter equations that describe the choice of recreation site or demand functions for site visits.[48] This approach is clearly useful if one wishes to link the valuation study to pollution control poli-

[47] While some studies have attempted to take the latency period and number of life-years saved into account (Josephine Mauskopf 1987), this is not the general practice (Cropper and Portney 1990).

[48] This approach is also used when the recreation activity studied is swimming or viewing, activities where perceptions of water quality are likely to be linked to water clarity and odor. It has, for example, been applied in studies of beach visits in Boston (Bockstael, Hanemann, and Kling 1987) and lake visits in Wisconsin (George Parsons and Kealy 1990).

cies, such as policies to reduce biochemical oxygen demand (BOD), a measure of the oxygen required to neutralize organic waste. A second approach is to relate site visits (or choice of site) to fish catch. Fish catch is clearly more closely associated with motives for visiting a site than is dissolved oxygen; however, it must be linked to changes in the fish population, which must, in turn, be linked to changes in ambient water quality.

A third approach is to treat changes in water quality as effectively eliminating or creating recreation sites. This approach has been used in valuing the effects of acid rain on fishing in Adirondack lakes: reductions in pH below certain thresholds have been treated as eliminating acres of surface area for fishing of particular species (John Mullen and Frederic Menz 1985). It is also the approach used by Vaughan and Russell (1982) in valuing the benefits of the Clean Water Act. They treat the benefits of moving all point sources to the Best Practical Control Technology Currently Available (BPT) as an increase in the number of acres of surface water that support game fish (bass, trout) as opposed to rough fish (carp, catfish). The Clean Water Act is thus viewed as increasing the number of recreation sites, rather than raising fish catch at existing sites.

Regardless of the form of water recreation valued, an improvement in water quality has two effects: it increases the utility of people who currently use the resource, and it may increase participation rates (number of days spent fishing). Varying parameter models that value changes in water quality or fish catch using the shift in demand for site visits (see Figure 2) capture both effects. Discrete choice models measure the effect of a quality improvement on a given recreation day, but do not estimate the effect of quality changes on the total number of days spent fishing; however, these models are typically used in conjunction with models that predict the total number of trips. Treating changes in water quality as altering the supply of available sites captures participation effects but not improvements in quality at existing sites.

In addition to travel cost models, contingent valuation studies have been used to value improvements in fish catch or water quality. Because it is difficult to ask consumers to value changes in dissolved oxygen levels or fecal coliform count—another measure of water quality—without linking these water quality measures to the type of activities they support, many CVM studies use the RFF Water Quality Ladder (Vaughan and Russell 1982), which relates a water quality index to the type of water use—boating, fishing (rough fish), fishing (game fish), swimming—that can be supported by various levels of the index. It is these activity levels that are valued by respondents. The water quality ladder has been used both to value water quality at specific sites (e.g., the Monongahela River, by V. Kerry Smith and Desvousges 1986a) and at all sites throughout the country (Carson and Mitchell 1988).

It is interesting to compare estimates of the value of water quality improvements obtained by the travel cost and contingent valuation approaches. Carson and Mitchell (1988) report that households are, on average, willing to pay $80 per year (in 1983 dollars) for an improvement in water quality throughout the U.S. from boatable to fishable (capable of supporting game fish). V. Kerry Smith and Desvousges (1986a) report a mean value of $25 per household for the same improvement in a five-county region in western Pennsylvania. The difference between these estimates reflects the fact that non-use values are important: households care about clean water in areas where they do not live. Even the $25 estimate for western Pennsylvania reflects nonuse values, since only one-third of the households surveyed engaged in some form of water based recreation.

Because they do not capture nonuse values, travel cost estimates of the value of improving water quality are not directly comparable with those obtained using the CVM. Using a varying parameter model, V. Kerry Smith and Desvousges (1986a) find the value of an improvement in water quality from boatable to fishable to be between $0.06 and $30.00 per person per day ($1983) for 30 Army Corps of Engineers sites. This value may be contrasted with estimates of $5 to $10 per person per day ($1983) obtained by Vaughan and Russell.

The preceding discussion suggests two problems that arise in valuing water quality benefits that do not arise in valuing health effects. The first is an aggregation problem. Suppose that one wishes to value the benefits of water quality improvements in a river basin, and suppose that the travel cost approach is used to measure use values associated with an improvement in dissolved oxygen or fish catch. The nonuse values associated with these improvements could be measured using a contingent valuation study. However, while the responses of nonusers could be added to values obtained from the travel cost approach, it would, in practice, be hard to separate use from nonuse values in the responses of fishermen.

The second problem is one of transferring results from a water quality study done in one geographic area to another area. While one can easily control for differences in willingness to pay in the two regions associated with differences in income and population, the value of water quality improvements is also likely to vary with the particular aesthetic and other characteristics of the region—and such characteristics are intrinsically hard to measure. Thus, whereas one can value a day of coughing independently of location, it is harder to value a generic fishing day.

This raises important questions concerning priorities for research in the area of recreation benefits.[49] Future research can proceed using a contingent valuation approach in which use and nonuse values are elicited simultaneously for sites in the respondent's region. The problem here is to have the respondent value an improvement to recreation that is sufficiently specific that it can be related to changes in pH levels from acid rain or changes in levels of dissolved oxygen associated with the adoption of BPT. The advantage of this approach is that it would capture both use and nonuse values. The advantage of the travel cost approach is that it could use endpoints more closely related to pollution (such as dissolved oxygen); however, it would not yield estimates of nonuse values.

3. *The Visibility Benefits of Pollution Control.* Reductions in air pollution, by increasing visibility, may improve the quality of life in urban areas as well as at recreation sites. Since the number of persons affected by improvements in visibility is large—at least as great as the number of persons whose health is affected by air pollution—the potential value of such benefits is great.

One can view the results of hedonic property value studies performed in the 1970s and early 1980s as evidence that people value the visibility benefits of pollution control. In these studies housing prices were regressed on measures of ambient air quality such as particulates or sulfates, which are negatively correlated

[49] It should be emphasized that, while there exist several dozen studies of water quality benefits in a recreation context, many studies analyze the same data. Thus, empirical estimates of water quality benefits exist for only a few areas of the country—lakes in Wisconsin and the Adirondacks, beaches in Boston and on the Chesapeake Bay, recreation sites in western Pennsylvania.

with visibility. The studies, most of which found significant negative effects of air pollution on housing prices, thus provide indirect evidence that people are willing to pay for improved visibility.[50] For example, John Trijonis et al. (1984) estimated based on differences in housing prices that households in San Francisco were willing, on average, to pay $200 per year for a 10 percent improvement in visibility.

The difficulty in using these studies to estimate benefits, however, is that the coefficient of air pollution (or visibility) captures all reasons why households may prefer to live in nonpolluted areas—including both improved health and reduced soiling. Indeed, the reason why property value studies have become less popular as a method of valuing the benefits of pollution control is that it is difficult to know what the pollution coefficient captures and, therefore, difficult to aggregate benefit estimates obtained from these studies with those obtained from other approaches. Such aggregation is necessary because residential property value studies capture benefits only at home and not at the other locations the household frequents.

For these reasons contingent valuation seems the most promising method for valuing visibility. Because visibility benefits vary regionally, CVM studies can most usefully be classified according to whether they measure urban visibility benefits or benefits at recreation sites, and according to whether the locations studied are in the Eastern or in the Western United States. The former distinction is important because visibility benefits at recreation sites—especially national parks—are likely to have a substantial nonuse component; consequently, the relevant population for which benefits are computed may be considerably larger than for urban visibility benefits. The East/West distinction is important both because of differences in baseline visibility and because of qualitative differences in the nature of visibility impairments, e.g., haze versus brown cloud.

There are two key problems in any contingent valuation study of visibility. One is presenting changes in visibility that are both meaningful to the respondent and that can be related to pollution control policies. The other is separating the respondent's valuation of health effects from his valuation of visibility changes.

Most CVM studies define increased visibility as an improvement in visual range—the distance at which a large, black object disappears from view. Visual range is both correlated with people's perceptions of visibility and with ambient concentrations of certain pollutants (fine nitrate and sulfate aerosols). Differences in visual range are presented in a series of pictures in which all other conditions—weather, brightness, the objects photographed—are, ideally, kept constant.

It has long been recognized (Brookshire et al. 1979) that, in responding to such pictures, people assume that the health effects of pollution diminish as visibility improves. Health effects are therefore inherently difficult to separate from visibility changes. The best way to handle this problem is to ask respondents what they assume health effects to be and then to control for these effects.

Unfortunately, existing CVM studies of visibility benefits—especially those for urban areas—have failed to treat the issues raised above in a satisfactory manner. With this limitation in mind, it is nonetheless of interest to contrast the magnitude of benefits associated with improvements in urban air quality with estimates obtained from hedonic property

[50] Freeman (1979a) provides an excellent summary of early studies.

value studies. Studies of visibility improvements in eastern U.S. cities (Tolley et al. 1986a; Douglas Rae 1984) have estimated that households would pay approximately $26 annually for a 10 percent improvement in visibility.[51] Loehmann Boldt, D., and Chaikin, K. (1981) reports an annual average willingness to pay per household of $101 for a 10 percent improvement in visibility in San Francisco. Both figures are considerably lower than estimates implied by property value studies.

Studies in recreation areas have focused on major national parks, including the Grand Canyon (Decision Focus 1990; Schulze and Brookshire 1983), because of the possibility of large nonuse values attached to visibility benefits at these sites. Two conclusions emerge from these studies. First, nonuse values appear to be large relative to use values. Use values associated with an improvement in visibility at the Grand Canyon from 70 to 100 miles are under $2.00 per visitor party per day ($1988) (Schulze and Brookshire 1983; K. K. MacFarland et al. 1983). By contrast, Schulze and Brookshire found that a random sample of households were willing to pay $95 per year ($1988) to prevent a deterioration in visibility at the Grand Canyon from the 50th percentile to the 25th percentile.

Second, the embedding, or superadditivity, problem is potentially quite serious. This refers to the fact that, in general, an individual's willingness to pay for simultaneous improvements in visibility at several sites should be less than the sum of his willingness to pay for isolated improvements at each site (Hoehn and Randall 1989). In a follow-up study to Schulze and Brookshire (1983), Tolley et al. (1986a) found respondents were willing to pay only $22 annually for the same visibility improvement at the Grand Canyon when this was valued at the same time as visibility improvements in Chicago (the site of the interviews) and throughout the East coast.

4. *The Ecological Benefits of Pollution Control.*[52] By the ecological benefits of pollution control, we mean reduced pollution of animal and plant habitats, such as rivers, lakes, and wetlands. Because the benefits of clean water to recreational fisherman or larger populations of deer to hunters are captured in recreation studies, the benefits discussed in this section are the nonuse benefits associated with reduced pollution of ecosystems.

It should be clear to the reader that valuing this category of benefits poses serious conceptual problems. One is defining the commodity to be valued. Does one value reductions in pollution concentrations, increases in animal populations, or some more subtle index of the health of an ecosystem? Two approaches can be taken here. The "top down" approach asks the respondent to value the preservation of an ecosystem, such as 100 acres of wetland (John Whitehead and Blomquist 1991). The "bottom up" approach values the preservation of particular species inhabiting the wetland, such as geese and other birds.

Regardless of the approach taken, several problems must be faced. One difficulty is defining what substitutes are assumed to exist, whether for a particular species or for a wetland (Whitehead and Blomquist 1991). Presumably the value

[51] This figure, reported by Chestnut and Rowe (1989), is an average of mean willingness to pay for each city surveyed by Tolley and Rae, based on Chestnut and Rowe's reanalysis of the data.

[52] Outside environmental economics, there is a considerable literature in environmental ethics that explores the issue of nonhuman rights and their policy implications. From this perspective, the economist's benefit-cost calculation with its wholly anthropocentric orientation is an excessively narrow and illegitimate framework for analysis. Kneese and Schulze (1985) provide an excellent treatment of this set of issues.

placed on the preservation of 10,000 geese depends on the size of the goose population. A related problem arises when programs are valued one at a time; in general, the value attached to preserving several species at the same time is less than the sum of the values attached to preserving each species in isolation. This implies that the totality of what is to be preserved should be valued: one cannot compute this by summing the values attached to individual components.

To date, most studies of endangered species have valued individual species in isolation. For example, Bowker and Stoll (1988) estimate that households are, on average, willing to pay $22 per year ($1983) to preserve the whooping crane, while Boyle and Bishop (1987) find that non-eagle watchers are willing to spend $11 per year to preserve the bald eagle in the state of Wisconsin. These values are appropriate if one is considering a program to preserve either of these species in isolation; however, the values should not be added together if one is contemplating preserving both species.

Even if one decides to value a wetland (of given size) and defines the nature of substitutes, an important question remains: do people really have well-defined, or in the terminology of psychologists, "crystallized" values for these commodities? Since respondents in CVM studies are likely to be less familiar with ecological benefits than with health and recreation benefits, responses are likely to depend critically on the information given to respondents in the survey itself (Karl Samples, John Dixon, and Marcia Gown 1986). This problem, however, is widely recognized, and recent studies have taken pains to see how responses are influenced by the amount of information provided.

5. *The Agricultural Benefits of Pollution Control.* Although we have emphasized the nonmarket benefits of pollution control, some benefits accrue directly to firms, and can be measured by examining shifts in the supply curves for the affected outputs. The industries that are most subject to ambient air and water pollution are forestry, fishing, and agriculture. We focus on agriculture because it is the sector that is likely to experience the largest benefits from pollution control.

Reductions in ozone concentrations and, possibly, in acid rain, should increase the yields of field crops such as soybeans, corn, and wheat. In addition, reductions in greenhouse gases, to the extent that they prevent increases in temperature and decreases in precipitation in certain areas, should also increase crop yields.

In measuring the effects on agricultural output of changes in pollution concentrations or climate, two approaches can be taken. The damage function approach translates a change in environmental conditions into a yield change, assuming that farmers take no actions to mitigate the effects of the change. The yield change shifts the supply curve for the crop in question, and the corresponding changes in consumer and producer surpluses are calculated.[53] This is the predominant approach used thus far to analyze the effects of global climate change (Sally Kane, John Reilly, and Tobey 1991). It has also been used in some studies of the effects of ozone on field crops (Richard Adams, Thomas Crocker, and Richard Katz 1984; Raymond Kopp et al. 1985; Kopp and Krupnick 1987).

The averting behavior approach allows farmers to adjust to the change in pollution/climate by altering their input mix and/or by adjusting the number of acres

[53] In calculating the welfare effects of a shift in supply, one must be careful to take into account the effects of agricultural price support programs, which distort market prices. See Erik Lichtenberg and David Zilberman (1986).

planted. In some applications, a profit function is estimated in which the environmental pollutant enters as a parameter (James Mjelde et al. 1984; Philip Garcia et al. 1986). The value of the change in Q can then be computed directly from the profit function. If the resulting shift in supply is big enough to alter market price, the welfare effects of these price changes must also be computed.

A more common approach is to solve for the effect of the change in pollution on output using a mathematical programming model whose coefficients have not been econometrically estimated (Adams, Scott Hamilton, and Bruce McCarl 1986; Scott Hamilton, McCarl, and Adams 1985). The effect of output changes on price is then computed separately.

While benefit estimates that allow farmers to adjust to changes in pollution are clearly preferable on theoretical grounds to estimates that do not allow such adjustments, it is important to ask how much of a difference this is likely to make empirically, especially as the damage function approach is much easier to implement. For changes in temperature and precipitation, damages are likely to be greatly overstated if opportunities for mitigating behavior (e.g., irrigation) are ignored.[54] On the other hand, mitigating behavior does not seem to make a great deal of difference in the case of ozone damage (Scott Hamilton, McCarl, and Adams 1985).

Estimates of annual damage to field crops from a 25 percent increase in ozone are in the neighborhood of $2 billion ($1980)—not negligible, but small relative to estimates of health damages. It is also interesting to note that most of these damages are borne by consumers. Producers in most cases gain from yield decreases due to the resulting increases in prices!

Kane, Reilly, and Tobey (1991) obtain similar results when estimating the welfare effects of global climate change on agriculture: reductions in the yields of field crops (wheat, corn, soybeans, and rice) in the U.S., Canada, China, and the USSR benefit producers worldwide due to increases in commodity prices. Consumers, however, lose. Thus, although the aggregate losses to producers and consumers worldwide are small (about one-half of one percent of world GDP), food-importing countries such as China suffer large welfare losses (equal to 5.5 percent of GDP) while food exporters such as Argentina enjoy welfare gains.

E. *Measuring the Costs of Pollution Control*

Table 1, which lists the costs of the major environmental statutes, may give the reader the impression that measuring the costs of pollution control is a straightforward matter. Such is not the case.

To begin with, the costs of pollution control must be measured using the same concepts that are used to measure the benefits of pollution control: the change in consumer and producer surpluses associated with the regulations and with any price and/or income changes that may result. The figures in Table 1 represent, for the most part, expenditures on cleaner fuels or abatement control equipment by firms. They do not represent the change in firms' profits, and thus ignore any adjustments firms may make to these expenditures. The figures also ignore the price and output effects associated with reducing emissions. At the very least, one would want to take into account the price changes likely to result within a sector because of environmental regulations—for example, one would

[54] We base this statement on the results of the RFF MINK project (Norman Rosenberg et al. 1990), which examines damages associated with climate change—specifically, a return to the climate of the dust bowl—in Missouri, Iowa, Nebraska, and Kentucky, under alternate adjustment scenarios.

want to measure the welfare effects of an increase in electricity prices resulting from the 10 million ton reduction in SO_2 emissions by electric utilities projected under the 1990 Amendments to the Clean Air Act.

We note that, at least in the short run, the effect of ignoring these adjustments is to overstate the cost of environmental regulations. Abatement expenditures overstate the loss in firms' profits if firms can pass on part of their cost increase to consumers. Consumers in turn can avoid some of the welfare effects of price increases of "dirty" goods by substituting "clean" goods for "dirty" ones.

When environmental regulations affect sectors, such as electricity production, that are important producers of intermediate goods, it may be important to measure the impacts that environmental regulations have throughout the economy. Computable general equilibrium models, preferably those in which supply and demand functions have been econometrically estimated, may be needed to measure correctly the social costs of environmental regulation.

Michael Hazilla and Kopp (1990) have used an econometrically estimated CGE model of the U.S. economy to compute the social costs of the Clean Air and Clean Water Acts, as implemented in 1981. The effects of these regulations on firms are modeled as an upward shift in firms' cost functions, to which firms can adjust by altering their choice of inputs and outputs. It is interesting to contrast the estimates of social costs obtained from this approach with EPA's estimates of compliance costs. The EPA estimated the costs of complying with the Clean Air and Clean Water Acts in 1981 to be $42.5 billion (1981 dollars). Hazilla and Kopp estimate the costs to be $28.3 billion; the lower figure reflects the substitution possibilities that the expenditure approach ignores.

In the long run, however, the social costs of the Clean Air and Clean Water Acts exceed simple expenditure estimates because of the effects of decreases in income on saving and investment. In their analysis of the effects of environmental regulation on U.S. economic growth, Dale Jorgenson and Peter Wilcoxen (1990a) measure this effect. Using a CGE model of the U.S. economy, they estimate that mandated pollution controls reduced the rate of GNP growth by .191 percentage points per annum over the period 1973–85.

V. *The Costs and Benefits of Environmental Programs*

The value of a symptom-day or a statistical life is, of course, only one component in evaluating a pollution control strategy. To translate unit benefit values into the benefits of an environmental program requires three steps: (1) the emissions reduction associated with the program must be related to changes in ambient air or water quality; (2) the change in ambient environmental quality must be related to health or other outcomes through a dose-response function; (3) the health or nonhealth outcomes must be valued. The information required for the first two tasks is considerable, especially if one wants to evaluate a major piece of legislation such as the Clean Air Act or Clean Water Act.

In this section we review attempts to estimate the benefits and costs of environmental programs. Of central interest are cases in which benefit-cost analyses have actually been used in setting environmental standards; in addition, we discuss instances in which such analyses have not been used but should be. This leads naturally to a discussion of priorities for research in the area of benefit and cost measurement.

A. *The Use of Benefit-Cost Analysis in Setting Environmental Standards*

Executive Order 12291, signed in 1981, requires that benefit-cost analyses be performed for all major regulations (defined as those having annual costs in excess of $100 million). Furthermore, the order requires, *to the extent permitted by law*, that regulations be undertaken only if the benefits to society exceed the costs.

One consequence of Executive Order 12291 is the undertaking of benefit-cost analyses for all major environmental regulations; however, the extent to which benefits and costs can be considered in making regulations is limited by the enabling statutes. Of the major environmental statutes only two, the Toxic Substances Control Act (TSCA) and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) explicitly require that benefits and costs be weighed in setting standards.[55] Some standards—specifically, those pertaining to new sources under the Clean Air Act and to the setting of effluent limitations under the Clean Water Act—allow costs to be taken into account, but do not suggest that benefits and costs be balanced at the margin. In contrast, the National Ambient Air Quality Standards and regulations for the disposal of hazardous waste under RCRA and CERCLA are to be made without regard to compliance costs.

In spite of these limitations, benefit-cost analyses have been used in EPA's rulemaking process since 1981. Between February of 1981 and February of 1986, EPA issued 18 major rules (USEPA 1987), including reviews of National Ambient Air Quality Standards for three pollutants—nitrogen dioxide, particulate matter, and carbon monoxide—effluent standards for water pollutants in the iron and steel and chemicals and plastics industries, and regulations to ban lead in gasoline, as well as certain uses of asbestos.[56] Regulatory Impact Analyses (RIAs) were prepared for 15 of these rules.

In five of the RIAs, both benefits and costs were monetized; however, benefits could legally be compared with costs only in the case of lead in gasoline. In this case, the benefits in terms of engine maintenance alone were judged to exceed the costs by $6.7 billion over the period 1985–92, and the regulation was issued. In two other cases—the PM standard and effluent limitations for iron and steel plants—the benefits exceeded the costs of the proposed regulation and the regulation was implemented, although EPA denied that it weighed benefits against costs in reaching its decision. The remaining cases are more difficult to evaluate. The clean water benefits of proposed effluent guidelines for chemicals and plastics manufacturers were judged to exceed regulatory costs in some sections of the country but not in others. EPA recommended that these guidelines be implemented. Of several alternative standards for emissions of particulate matter by surface coal mines, only one was found to yield positive net benefits, and these were small ($300,000). Eventually, no regulation was issued by EPA.

The preceding review suggests that benefit-cost analysis has not entirely been ignored in setting environmental standards, but its use has been selective. In part, this is the result of law—EPA was allowed to weigh benefits against costs for only 5 of the 18 major regulations that it issued between 1981 and

[55] Some portions of the Clean Air Act, specifically, those pertaining to aircraft emissions, motor vehicle standards and fuel standards, also require that marginal benefits and costs be balanced.

[56] A complete listing of the regulations may be found in USEPA (1987). Also included were regulations governing the disposal of used oil, and standards regarding land disposal of hazardous waste.

1986.[57] One could argue that the government should not invest resources in a full blown benefit-cost analysis if the results of such an analysis cannot be used in regulating the polluting activity. But this would be a mistake. Even where the explicit use of a benefit-cost test is prohibited, such studies can be informative and useful. In their own way, they are likely to influence the views of legislators and regulators. In particular, the issue is often one of amending standards—either raising them or lowering them. Benefit-cost information on such adjustments, although not formally admissible, may well have some impact on decisions to revise standards. In addition, simply demonstrating the feasibility and potential application of such studies may lead to their explicit introduction into the policy process at a later time.

B. *The Need for Benefit-Cost Analyses of Environmental Standards*

We turn now to a set of priorities for benefit-cost analyses of environmental regulation: which of existing environmental programs require closest scrutiny and what benefit techniques must be developed in order to perform these analyses? We begin with an enumeration of these programs, as we see them, and then offer some thoughts on the analysis of each of them.

There are, broadly, two areas in wbich careful benefit-cost analyses are most needed. One is for statutes whose total costs are thought to exceed their total benefits. A widely cited example is the Clean Water Act (CWA), which will soon be up for renewal. Freeman (1982) suggests that the recreational use values associated with the adoption of BPT are small, relative to the costs presented in Table 1. Justification for these standards must then rest on other grounds. A second example where costs may exceed benefits involves the extent of cleanup of Superfund sites under CERCLA. While the cost of cleaning up these sites is predicted to run into the hundreds of billions of dollars, the health benefits of these cleanups are thought by many to be modest (Curtis Travis and Carolyn Doty 1989). Current law does not require an explicit benefit-cost analysis of remedial alternatives at each Superfund site, but, in our view, it probably should.

The second general class of cases in which careful benefit-cost analyses are needed is where environmental standards are sufficiently stringent to push control efforts onto the steep portion of the marginal cost of abatement curve. Even though the total costs of these standards may exceed their total benefits (see Figure 4), society might experience a gain in welfare from relaxing the standard if the marginal benefits of abatement are considerably below the marginal costs at the level of the standard. In terms of Figure 4, we need to know whether the marginal benefit function is MB_2 or MB_1. There are several instances of actual policies that appear to fall within this class: (1) the ground-level ozone standard, in areas that are currently out of compliance with the standard; (2) certain provisions in RCRA for disposal of hazardous waste; and (3) the 1990 acid rain amendments to the Clean Air Act. In addition to these existing laws, proposals for significant reductions in CO_2 emissions may entail high marginal costs, suggesting a close scrutiny of benefits.

Turning first to the Clean Water Act, we note that evaluating the CWA will require computing the use (recreation) and nonuse (ecological) benefits of im-

[57] For the other four regulations where a comparison of costs and benefits was allowed—the three toxic substances (TSCA) regulations and the setting of emission standards for light duty trucks—benefits were quantified but not monetized. In the case of PCB's the cost per catastrophe avoided was computed; in the case of asbestos, the cost per life saved.

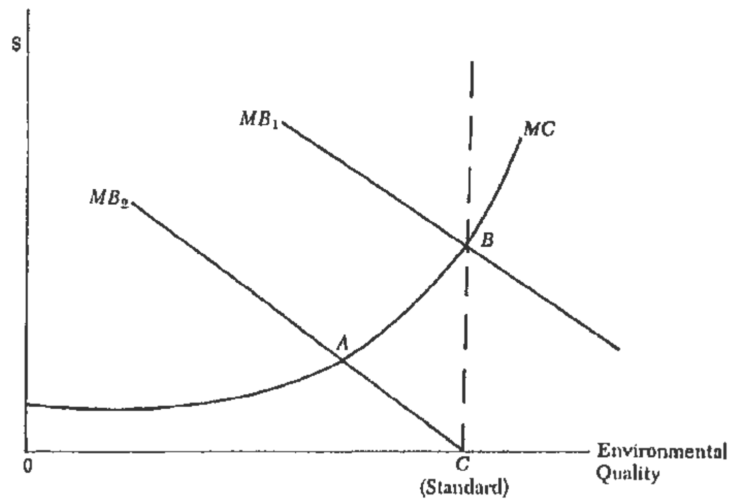

Figure 4. Welfare Loss from Setting Incorrect Standards

proved water quality. As we noted above, one can either use a contingent valuation approach that captures both values, or one can attempt to capture use values using travel cost methods and measure nonuse values separately. Whichever approach is used, we emphasize the regional character of the costs and benefits of improved water quality; benefit estimates must, in consequence, be available at this level of disaggregation. The contingent valuation method avoids two problems inherent in the use of travel cost models. First, unless the transferability problem can be solved, travel cost models will have to be estimated for each river or lake throughout the U.S.! And, second, if a contingent valuation survey of nonuse values is to be added to travel cost measures of use values, it may be hard to get users to separate use from nonuse values.

A key issue in valuing the benefits of Superfund cleanups is how to value health risks—usually risks of cancer—that will not occur until the distant future. Many Superfund sites pose very low health risks today, primarily because there is no current route of exposure to toxic waste. People could, however, be exposed to contaminated soils or groundwater if substances were to leak from storage containers in the future. This involves valuing future risks to persons currently alive as well as to persons yet unborn. While some research has been done in this area (Mauskopf 1987; Cropper and Portney 1990; Cropper and Sussman 1990), there are few empirical studies that examine either the value that people place on reducing future risks to themselves or the rate at which they discount lives saved in future generations. Estimates of these values are also crucial if one is to analyze regulations governing the current disposal of hazardous waste under RCRA, as well as other regulations that affect exposure to carcinogens (e.g., air toxics and pesticide regulations).

An additional problem is how to incorporate uncertainty regarding estimates of health risks into the analysis. While most valuation studies treat the probability of an adverse outcome as certain, in reality there is great uncertainty about health risks, especially the risk of contracting cancer from exposure to environmental carcinogens. This uncertainty has two sources: uncertainty about actual exposures received, and uncertainty about the effects of a given exposure.[58] The standard procedure in risk assessments is to "correct" for this uncertainty by presenting a point estimate based on very conservative assumptions (Nichols and Richard Zeckhauser 1986). It would, however, be more appropriate to incorporate the distribution of cancer risk into the analysis.

Existing estimates of the marginal costs and marginal benefits of achieving the one-hour ozone standard in areas that are currently out of attainment suggest that marginal costs exceed marginal benefits (Krupnick and Portney 1991). Estimates of the health benefits of ozone control have, however, focused on the value of reducing restricted-activity or symptom days. There is some evidence that ozone may exacerbate the rate at which lung tissue deteriorates, contributing to chronic obstructive lung disease (COPD). Since, for healthy individuals, the probability of contracting COPD is uncertain, what must be valued is a change in the risk of contracting chronic lung disease corresponding to a change in ozone concentrations.

The objective of the provisions of the 1990 Amendments to the Clean Air Act aimed at reducing SO_2 and NO_2 is to reduce acid rain, primarily in the Eastern U.S. and Canada. Although the 10-million-ton reduction in sulfur emissions specified in the amendments is likely to have some health benefits, most of the anticipated benefits are ecological or recreational, resulting from an increase in the pH of lakes.[59] There are also likely to be visibility benefits (reduced haze) in the Eastern U.S. This underscores the need for better estimates of the value of improved visibility, especially in urban areas. It will also be necessary to measure the ecological benefits associated with reduced acid rain, especially as these are likely to differ qualitatively from the ecological benefits associated with the CWA.

Finally, we note that in the area of global climate change, considerable attention has been devoted to measuring the costs of reducing greenhouse gas emissions, especially through the use of a tax on the carbon content of fuels (Jorgenson and Wilcoxen 1990b). Little, however, is known about the benefits of reducing greenhouse gases, even if one assumes that the link between CO_2 and climate change is certain.[60]

The benefits of preventing these climate changes differ from the benefits associated with conventional air and water pollutants in two respects. First, many—though by no means all—of the effects of climate change are likely to occur through markets. These include effects on agriculture and forestry, as well as changes in heating and cooling costs. While this should make benefits easier to measure, the problem is that the effects of CO_2 emissions are not likely to be felt for decades. This implies that valuing such damages is difficult. A damage function approach, which ignores adaptation possibilities, is clearly inappropriate; however, predicting technological possibilities for adaptation is not easy.

Second, the benefits of reducing greenhouse gases will not be felt until the next century. The problem here is that, even at a discount rate of only 3

[58] Estimates of the effect of a given exposure usually come from rodent bioassays, which are used to estimate a dose-response function. In addition to uncertainty regarding the parameters of the dose-response function, there is uncertainty as to how these estimates should be extrapolated from rodents to man.

[59] For a dissenting view see Portney (1990).

[60] A useful beginning here is the work of William Nordhaus (1990).

percent, one dollar of benefits received 100 years from now is worth only 5 cents today. This problem has typically been addressed by suggesting that benefits should be discounted at a very low rate, if at all. An alternative approach is to make transfers to future generations to compensate them for our degradation of the environment, rather than to alter the discount rate.

C. *The Distribution of Costs and Benefits*

In addition to examining the costs and benefits of environmental legislation, it is of interest to know who pays for pollution abatement and who benefits from it. Typically, studies of the distributional effects of environmental programs emphasize the distribution of benefits and costs by income class.

To determine how the benefits of environmental programs are distributed across different income classes, we must measure how the programs alter the physical environmeuts of differeut income groups. In one study of the distributional effects of programs aimed at raising the level of national air quality, Leonard Gianessi, Peskin, and Edward Wolff (1979) found striking locational differentials in benefits; not surprisingly, most of the benefits from efforts to improve air quality are concentrated in the more industrialized urban areas (largely the heavily industrialized cities of the East) with fewer benefits accruing to rural residents. Even within metropolitan areas, air quality may differ substantially. Since the poor often live in the most polluted parts of urban areas, they might be thought to be disproportionately large beneficiaries of programs that reduce air pollution—and there is evidence that this is, indeed, the case (Asch and Seneca 1978; Jeffrey Zupan 1973). While this may be true, certain indirect effects can follow that offset such benefits. For example, cleaner air in what was a relatively dirty area may increase the demand for residences there and drive up rents, thereby displacing low-income renters. All in all, this is a complicated issue. At any rate, Gianessi, Peskin, and Wolff find that within urban areas the distribution of benefits may be slightly pro-poor, but, as we shall see next, this is likely to be offset (or more than offset) by a regressive pattern of the costs of these programs.[61]

We are on somewhat more solid ground on the distribution of the costs of environmental programs (G. B. Christainseu and Tietenberg 1985). There exist data on the costs of pollution control by industry with which one can estimate how costs have influenced the prices of various classes of products and how, in turn, these increased prices have reduced the real incomes of different income classes. In one early study of this kind, Gianessi, Peskin, and Wolff (1979) examined the distributive pattern of the costs of the Clean Air Act and found that lower-income groups bear costs that constitute a larger fraction of their income than do higher-income classes. (See also Nancy Dorfman and Arthur Snow 1975; Gianessi and Peskin 1980.) Three independent studies of automobile pollution control costs all reach similar findings of regressivity (Dorfman and Snow 1975; Harrison 1975; Freeman 1979b).

In a more recent study, Robison (1985) uses an input-output model to estimate the distribution of costs of industrial pollution abatement. Assuming that the costs of pollution control in each industry are passed on in the form of higher prices, Robison traces these price in-

[61] Moreover, there is some persuasive evidence from observed voting patterns on proposed environmental measures (Robert Deacon and Perry Shapiro 1975; Fischel 1979) indicating that higher income individuals are willing to pay more for a cleaner environment than those with lower incomes.

creases through the input-output matrix to determine their impact on the pattern of consumer prices. Robison's model divides individuals into twenty income classes. For each class, estimates are available of the pattern of consumption among product groups. This information, together with predictions of price increases for each product, is used to estimate the increase in the prices of goods consumed by each income group. Robison finds that the incidence of control costs is quite regressive. Costs as a fraction of income fall over the entire range of income classes; they vary from 0.76 percent of income for the lowest income class to 0.16 percent of income for the highest income class.

It is true that these studies relate to existing environmental programs and do not measure directly the potential distributional effects of a system of economic incentives such as effluent fees. But our sense is that the pattern of control costs across industries would be roughly similar under existing and incentive-based programs. It is the same industries under both regimes that will have to undertake the bulk of the abatement measures. Our conjecture thus is that the pattern of costs for our major environmental programs is likely to be distinctly regressive in its incidence, be they of the command-and-control or incentive-based variety.

While the distributional effects of environmental programs may not be altogether salutary, we do not wish to exaggerate their importance. We emphasize that the primary purpose of environmental programs is, in economic terms, an efficient allocation of resources. Environmental measures, as Freeman (1972) has stressed, are not very well suited to the achievement of redistributional objectives. But an improved environment provides important benefits for all income classes—and we will be doing no groups a favor by opposing environmental programs on distributional grounds. At the same time, there are opportunities to soften some of the more objectionable redistributive consequences of environmental policies through the use of measures like adjustment assistance for individuals displaced from jobs in heavily polluting industries and the reliance on the more progressive forms of taxation to finance public spending on pollution control programs.

VI. *Environmental Economics and Environmental Policy: Some Reflections*

As suggested by the lengthy (and only partial) list of references and citations in this survey, environmental economics has been a busy field over the past two decades. Environmental economists have reworked existing theory, making it more rigorous and clearing up a number of ambiguities; they have devised new methods for the valuation of benefits from improved environmental quality; and they have undertaken numerous empirical studies to measure the costs and benefits of actual or proposed environmental programs and to assess the relative efficiency of incentive-based and CAC policies. In short, the "intellectual structure" of environmental economics has been both broadened and strengthened since the last survey of the field by Fisher and Peterson in this *Journal* in 1976.

But what about the contribution of environmental economics to the design and implementation of environmental policy? This is not an easy question to answer. We have seen some actual programs of transferable emissions permits in the United States and some use of effluent charges in Europe. And with the enactment of the 1990 Amendments to the Clean Air Act, the U.S. has introduced a major program of tradable allowances to control sulfur emissions—moving this country squarely into the use of incentive-based approaches to regulation in at least one area of environmental policy.[62] But, at the same time, effluent charge and marketable permit programs are few in number and often bear only a modest resemblance to the pure programs of economic incentives supported by economists. As we noted in the introduction, certain major pieces of environmental legislation prohibit the use of economic tests for the setting of standards for environmental quality, while other directives require them! The record, in short, is a mixed and somewhat confusing one: it reveals a policy environment characterized by a real ambivalence (and, in some instances, an active hostility) to a central role for economics in environmental decision making.[63]

What is the potential and the likelihood of more attention to the use of economic analysis and economic incentives in environmental management? It is easy to be pessimistic on this matter. There is still some aversion, both in the policy arena and across the general public, to the use of "market methods" for pollution control. While we were working on this survey, one of the leading news magazines in the U.S. ran a lengthy feature story entitled "The Environment: Cleaning Up Our Mess—What Works, What Doesn't, and What We Must Do to Reclaim our Air, Land, and Water" (Gregg Easterbrook 1989, in *Newsweek*). A central argument in the article is that the attempt to place environmental policy on a solid "scientific" footing has been a colossal error that has handcuffed efforts to get on with pollution control. Proceeding "on the assumption that environmental protection is a social good transcending cost-benefit calculations" (p. 42), Easterbrook argues that we should not place a high priority on scientific work on the complicated issues of measuring benefits and costs and of providing carefully designed systems of incentives, but should get on with enacting pollution control measures that are technologically feasible. In short, we should control what technology enables us to control without asking too many hard questions and holding up tougher legislation until we know all the answers.

Such a position has a certain pragmatic appeal. As we all know, our understanding of complicated ecological systems and the associated dose-response relationships is seriously incomplete. And as our survey has indicated, our ability to place dollar values on improvements in environmental quality is limited and imprecise. Nevertheless, we have some hard choices to make in the environmental arena—and whatever guidance we can obtain from a careful, if imprecise, consideration of benefits and costs should not be ignored.

[62] Under this provision, the U.S. will address the acid rain problem by cutbacks in sulfur emissions over the next decade of 10 million tons (about a 50 percent reduction). This is to be accomplished through a system of tradable allowances under which affected power plants will be allowed to meet their emissions reductions by whatever means they choose—including the purchase of "excess" emissions reductions from other sources that choose to cut back by more than their required quota. Also noteworthy is the U.S. procedure to implement reductions in chlorofluorocarbon emissions under the Montreal Protocol. Under this measure, EPA has effectively grandfathered the U.S. quota among existing producers and importers; from these baselines, firms are allowed to trade allowances (Hahn and McGartland 1989).

[63] Some recent studies of actual environmental decision making are consistent with this "mixed" view. Magat, Krupnick, and Harrington (1986), for example, in a study of EPA determination of effluent standards under the Clean Water Act Amendments of 1972, found that "simple rules based either on economic efficiency or the goal of distributional equity did not dominate the rulemaking process" (p. 154). Their analysis did find that standards across industry subcategories reflected to some extent differences in compliance costs among firms. In contrast, Cropper et al. (1992) find that EPA decisions on pesticide regulation have, in fact, reflected a systematic balancing of environmental risks and costs of control. Economic factors, it appears, have mattered in some classes of decisions and not in others.

We stress, moreover, that the role for economic analysis in environmental policy making is far more important now than in the earlier years of the "environmental revolution." When we set out initially to attack our major pollution problems, there were available a wide array of fairly direct and inexpensive measures for pollution control. We were, in short, operating on relatively low and flat segments of marginal abatement cost (MAC) curves. But things have changed. As nearly all the cost studies reveal, marginal abatement cost functions have the typical textbook shape. They are low and fairly flat over some range and then begin to rise, often quite rapidly. Both the first and second derivatives of these abatement cost functions are positive—and rapidly increasing marginal abatement costs often set in with a vengeance.

We now find ourselves operating, in most instances, along these rapidly rising portions of MAC functions so that decisions to cut pollution yet further are becoming more costly. In such a setting, it is crucial that we have a clear sense of the relative benefits and costs of alternative measures. It will be quite easy, for example, to enact new, more stringent regulations that impose large costs on society, well in excess of the benefits, health or otherwise, to the citizenry. As Portney (1990) has suggested, this may well be true of the new measures to control urban air pollution and hazardous air pollutants under the most recent Amendments to the Clean Air Act. Portney's admittedly rough estimates suggest that the likely range of benefits from these new provisions falls well short of the likely range of their cost.

Economic analysis can be quite helpful in getting at least a rough sense of the relative magnitudes at stake. This is not, we would add, a matter of sophisticated measures of "exact consumer surplus" but simply of measuring as best we can the relevant areas under crude approximations to demand curves (compensated or otherwise). In addition to measurement issues, this new setting for environmental policy places a much greater premium on the use of cost-effective regulatory devices, for the wastes associated with the cruder forms of CAC policies will be much magnified.[64]

In spite of the mixed record, it is our sense that we are at a point in the evolution of environmental policy at which the economics profession is in a very favorable position to influence the course of policy. As we move into the 1990s, the general political and policy setting is one that is genuinely receptive to market approaches to solving our social problems. Not only in the United States but in other countries as well, the prevailing atmosphere is a conservative one with a strong disposition toward the use of market incentives, wherever possible, for the attainment of our social objectives. Moreover, as we have emphasized in this survey, we have learned a lot over the past twenty years about the properties of various policy instruments and how they work (or do not work) under different circumstances. Economists now know more about environmental policy and are in a position to offer better counsel on the design of measures for environmental management.

This, as we have stressed, takes us from the abstract world of pure systems of fees or marketable permits. Environmental economists must be (and, we be-

[64] Following our earlier discussion of the Weitzman theorem, we note its implication for the issue under discussion here: a preference for price over quantity instruments. So long as there is little evidence of any dramatic threshold effects or other sources of rapid changes in marginal benefits from pollution control, the steepness of the MAC function suggests that regulatory agencies can best protect against costly error by adopting effluent fees rather than marketable emission permits (Hadi Dowlatabadi and Harrington 1989; Oates, Portney, and McGartland 1989).

lieve, are) prepared to come to terms with detailed, but important, matters of implementation: the determination of fee schedules, issues of spatial and temporal variation in fees or allowable emissions under permits, the life of permits and their treatment for tax purposes, rules governing the transfer of pollution rights, procedures for the monitoring and enforcement of emissions limitations, and so on. In short, economists must be ready to "get their hands dirty."

But the contribution to be made by environmental economists can be a valuable one. And there are encouraging signs in the policy arena of a growing receptiveness to incentive-based approaches to environmental management. As we noted in the introduction, both in the United States and in the OECD countries more generally, there have been recent expressions of interest in the use of economic incentives for protection of the environment. As we were finishing the final draft of this survey, the Council of the OECD issued a strong and lengthy endorsement of incentive-based approaches, urging member countries to "make a greater and more consistent use of economic instruments" for environmental management (OECD 1991).

Finally, we note the growing awareness and concern with global environmental issues. Many pollutants display a troublesome tendency to spill over national boundaries. While this is surely not a new issue (e.g., transnational acid rain), the thinning of the ozone shield and the prospect of global warming are pressing home in a more urgent way the need for a global perspective on the environment. The potential benefits and costs of programs to address these issues, particularly global warming, are enormous—and they present a fundamental policy challenge. The design and implementation of workable and cost-effective measures on a global scale are formidable problems, to put it mildly. And they call for an extension of existing work in the field to the development of an "open economy environmental economics" that incorporates explicitly the issues arising in an international economy linked by trade, financial, *and* environmental flows.[65]

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sworn before me this 17th day
of DECEMBER 2018

A Commissioner for taking Affidavits
within British Columbia

Prices *vs.* Quantities [1,2]

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I. INTRODUCTION

The setting for the problem under consideration is a large economic organization or system which in some cases is best thought of as the entire economy. Within this large economic organization resources are allocated by some combination of commands and prices (the exact mixture is inessential) or even by some other unspecified mechanism. The following question arises. For one particular isolated economic variable that needs to be regulated,[3] what is the best way to implement control for the benefit of the organization as a whole? Is it better to directly administer the activity under scrutiny or to fix transfer prices and rely on self-interested profit or utility maximization to achieve the same ends in decentralized fashion? This issue is taken as the prototype problem of central control which is studied in the present paper. There are a great many specific examples which fit nicely into such a framework. One of current interest is the question of whether it would be better to control certain forms of pollution by setting emission standards or by charging the appropriate pollution taxes.

When quantities are employed as planning instruments, the basic operating rules from the centre take the form of quotas, targets, or commands to produce a certain level of output. With prices as instruments, the rules specify either explicitly or implicitly that profits are to be maximized at the given parametric prices. Now a basic theme of resource allocation theory emphasizes the close connection between these two modes of control. No matter how one type of planning instrument is fixed, there is always a corresponding way to set the other which achieves the same result when implemented.[4] From a strictly theoretical point of view there is really nothing to recommend one mode of control over the other. This notwithstanding, I think it is a fair generalization to say that the average economist in the Western marginalist tradition has at least a vague preference toward indirect control by prices, just as the typical non-economist leans toward the direct regulation of quantities.

That a person not versed in economics should think primarily in terms of direct controls is probably due to the fact that he does not comprehend the full subtlety and strength of the invisible hand argument. The economist's attitude is somewhat more puzzling. Understanding that prices can be used as a powerful and flexible instrument for rationally allocating resources and that in fact a market economy automatically regulates itself in this manner is very different from being under the impression that such indirect controls are generally preferable for the kind of problem considered in this paper. Certainly a careful reading of economic theory yields little to support such a universal proposition.

1 *First version received August* 1973; *final version accepted January* 1974 (*Eds.*).

2 Many people have made helpful comments about a previous version of this paper. I would like especially to thank P. A. Diamond and H. E. Scarf for their valuable suggestions. The National Science Foundation helped support my research.

3 Outside the scope of this paper is the issue of *why* it is felt that the given economic activity must be regulated. There may be a variety of reasons, ranging all the way from political considerations to one form or another of market failure.

4 Given the usual convexity assumptions. Without convexity it may not be possible to find a price which will support certain output levels. In this connection it should be mentioned that non-convexities (especially increasing returns) are sometimes responsible for regulation in the first place.

Many economists point with favour to the fact that if prices are the planning instrument then profit maximization automatically guarantees total output will be efficiently produced, as if this result were of any more than secondary interest unless the prices (and hence total output) are optimal to begin with.[1] Sometimes it is maintained that prices are desirable planning instruments because the stimulus to obtain a profit maximizing output is built right in if producers are rewarded in proportion to profits. There is of course just as much motivation, e.g. to minimize costs at specified output levels so long as at least some fraction of production expenditures is borne by producers. With both modes of control there is clearly an incentive for self-interested producers to systematically distort information about hypothetical output and cost possibilities in the pre-implementation planning phase. Conversely, there is no real way to disguise the true facts in the implementation stage so long as actual outputs (in the case of price instruments) and true operating costs (in the case of quantity instruments) can be accurately monitored. For the one case the centre must ascertain *ceteris paribus* output changes as prices are varied, for the other price changes as outputs are altered.

A reason often cited for the theoretical superiority of prices as planning instruments is that their use allegedly economizes on information. The main thing to note here is that generally speaking it is neither easier nor harder to name the right prices than the right quantities because in principle exactly the *same* information is needed to correctly specify either. It is true that in a situation with many independent producers of an identical commodity, only a single uniform price has to be named by the centre, whereas in a command mode separate quantities must be specified for each producer. If such an observation has meaningful implications, it can only be within the artificial milieu of an iterative *tâtonnement* type of " planning game " which is played over and over again approaching an optimal solution in the limit as the number of steps becomes large. Even in this context the fact that there are less " message units " involved in each communication from the centre is a pretty thin reed on which to hang claims for the informational superiority of the price system. It seems to me that a careful examination of the mechanics of successive approximation planning shows that there is no principal informational difference between iteratively finding an optimum by having the centre name prices while the firms respond with quantities, or by having the centre assign quantities while the firm reveals costs or marginal costs.[2]

If there were really some basic intrinsic advantage to a system which employed prices as planning instruments, we would expect to observe many organizations operating with this mode of control, especially among multi-divisional business firms in a competitive

[1] An extreme example may help make this point clear. Suppose that fulfilment of an important emergency rescue operation demands a certain number of airplane flights. It would be inefficient to just order airline companies or branches of the military to supply a certain number of the needed aircraft because marginal (opportunity) costs would almost certainly vary all over the place. Nevertheless, such an approach would undoubtedly be preferable to the efficient procedure of naming a price for plane services. Under profit maximization, overall output would be uncertain, with too few planes spelling disaster and too many being superfluous.

[2] The " message unit " case for the informational superiority of the price system is analogous to the blanket statement that it is better to use dual algorithms for solving a programming problem whenever the number of primal variables exceeds the number of dual multipliers. Certainly for the superior large step decomposition type algorithms which on every iteration go right after what are presently believed to be the best instrument values on the basis of all currently available information, such a general statement has no basis. With myopic gradient methods it is true that on each round the centre infinitesimally and effortlessly adjusts exactly the number of instruments it controls, be they prices or quantities. But who can say *how many* infinitesimally small adjustments will be needed? Gradient algorithms are known to be a bad description of iterative planning procedures, among other reasons because they have inadmissably poor convergence properties. If the step size is chosen too small, convergence takes forever. If it is chosen too large, there is no convergence. As soon as a finite step size is selected on a given iteration to reflect a desire for quick convergence, the " message unit " case for prices evaporates. Calculating the *correct* price change puts the centre right back into the large step decomposition framework where on each round the problem of finding the best iterative prices is formally identical to the problem of finding the best iterative quantities. For discussion of these and various other aspects of iterative planning, see the articles of Heal [4], Malinvaud [5], Marglin [7], Weitzman [9].

environment. Yet the allocation of resources within private companies (not to mention governmental or non-profit organizations) is almost never controlled by setting administered transfer prices on commodities and letting self-interested profit maximization do the rest.[1] The price system as an allocator of internal resources does not itself pass the market test.[2]

Of course, all this is not to deny that in any *particular* setting there may be important *practical* reasons for favouring either prices or quantities as planning instruments. These reasons might involve ideological, political, legal, social, historical, administrative, motivational, informational, monitoring, enforcing, or other considerations.[3] But there is little of what might be called a system-free character.

In studying such a controversial subject, the only fair way to begin must be with the tenet that there is no *basic* or *universal* rationale for having a general predisposition toward one control mode or the other. If this principle is accepted, it becomes an issue of some interest to abstract away all " other " considerations in order to develop strictly " economic " criteria by which the comparative performance of price and quantity planning instruments might be objectively evaluated. Even on an abstract level, it would be useful to know how to identify a situation where employing one mode is relatively advantageous, other things being equal.

II. THE MODEL

We start with a highly simplified prototype planning problem. Amount q of a certain commodity can be produced at cost $C(q)$, yielding benefits $B(q)$.[4] The word " commodity " is used in an abstract sense and really could pertain to just about any kind of good from pure water to military aircraft. Solely for the sake of preserving a unified notation, we follow the standard convention that goods are desirable. This means that rather than talking about air pollution, for example, we instead deal with its negative—clean air.

Later we treat more complicated cases, but for the time being it is assumed that in effect there is just one producer of the commodity and no ambiguity in the notion of a cost curve. Benefits are measured in terms of money equivalents so that the benefit function can be viewed as the reflection of an indifference curve showing the trade-off between amounts of uncommitted extra funds and output levels of the given commodity. It is assumed that $B''(q)<0$, $C''(q)>0$, $B'(0)>C'(0)$, and $B'(q)<C'(q)$ for q sufficiently large.

[1] Strictly speaking, this conclusion is not really justified because there may be important externalities or increasing returns within an organization (they may even constitute its *raison d'être*). Nevertheless, the almost universal absence of internal transfer pricing within private firms strikes me as a rather startling contradiction with the often alleged superiority of indirect controls.

[2] About a decade ago, Ford and GM performed a few administrative trials of a limited sort with some decentralization schemes based on internal transfer prices. The experiments were subsequently discontinued in favour of a return to more traditional planning methods. See Whinston [10].

[3] As one example, if it happens to be the case that it is difficult or expensive to monitor output on a continuous scale but relatively cheap to perform a pass-fail litmus type test on whether a given output level has been attained or not, the price mode may be greatly disadvantaged from the start. The pollution by open-pit mining operations of nearby waterways presents a case in point. It would be difficult or impossible to record how much pollutant is seeping into the ground, whereas it is a comparatively straightforward task to enforce the adoption of one or another level of anti-pollution technology. Another realistic consideration arises when we ask who determines the standards under each mode. For example, if an agency of the executive branch is empowered to regulate prices but the legislature is in charge of setting quantities, that by itself may be important in determining which mode is better for controlling pollution. The price mode would have greater flexibility, but might carry with it more danger of caving in to special interest groups. As yet another realistic consideration, equity arguments are sometimes put forward in favour of price (the supposed " justice " of a uniform price to all) or quantity (equal sharing of a deficit commodity) control modes.

[4] It might be thought that an equivalent approach would be to work with demand and supply curves, identifying the consumers' (producers') surplus area under the demand (supply) curve as benefits (costs) or, equivalently, the demand (supply) curve as the marginal benefit (cost) function. The trouble with this approach is that it tends to give the misleading impression that the market left to itself could solve the problem, obscuring the fact that some key element of the standard competitive supply and demand story is felt to be missing in the first place.

The planning problem is to find that value q^* of q which maximizes

$$B(q)-C(q).$$

The solution must satisfy

$$B'(q^*) = C'(q^*).$$

With

$$p^* \equiv B'(q^*) = C'(q^*),$$

it makes no difference whether the planners announce the optimal price p^* and have the producers maximize profits

$$p^*q-C(q)$$

or whether the centre merely orders the production of q^* at least cost. In an environment of complete knowledge and perfect certainty there is a formal identity between the use of prices and quantities as planning instruments.

If there is any advantage to employing price or quantity control modes, therefore, it must be due to inadequate information or uncertainty. Of course it is natural enough for planners to be unsure about the precise specification of cost and benefit functions since even those most likely to know can hardly possess an exact account.

Suppose, then, that the centre perceives the cost function only as an estimate or approximation. The stochastic relation linking q to C is taken to be of the form

$$C(q, \theta),$$

where θ is a disturbance term or random variable, unobserved and unknown at the present time. While the determination of θ could involve elements of genuine randomness,[1] it is probably more appropriate to think primarily in terms of an information gap.

Even the engineers most closely associated with production would be unable to say beforehand precisely what is the cheapest way of generating various hypothetical output levels. How much murkier still must be the centre's *ex ante* conception of costs, especially in a fast moving world where knowledge of particular circumstances of time and place may be required. True, the degree of fuzziness could be reduced by research and experimentation but it could never be truly eliminated because new sources of uncertainty are arising all the time.[2]

Were a particular output level really ordered in all seriousness, a cost-minimizing firm could eventually grope its way toward the cheapest way of producing it by actually testing out the relevant technological alternatives. Or, if an output price were in fact named, a profit maximizing production level could ultimately be found by trial and error. But this is far from having the cost function as a whole knowable *a priori*.

While the planners may be somewhat better acquainted with the benefit function, it too is presumably discernable only tolerably well, say as

$$B(q, \eta)$$

with η a random variable. The connection between q and B is stochastic either because benefits may be imperfectly known at the present time or because authentic randomness may play a role. Since the unknown factors connecting q with B are likely to be quite different from those linking q to C, it is assumed that the random variables θ and η are independently distributed.

As a possible specific example of the present formulation, consider the problem of air pollution. The variable q could be the cleanliness of air being emitted by a certain type of source. Costs as a function of q might not be known beyond doubt because the technology, quantified by θ, is uncertain. At a given level of q the benefits may be unsure since they depend among other things on the weather, measured by η.

1 Like day-to-day fluctuations.
2 For an amplification of some of these points, see Hayek [3].

Now an *ideal* instrument of central control would be a contingency message whose instructions depend on which state of the world is revealed by θ and η. The ideal *ex ante* quantity signal $q^*(\theta, \eta)$ and price signal $p^*(\theta, \eta)$ are in the form of an entire schedule, functions of θ and η satisfying

$$B_1(q^*(\theta, \eta), \eta) = C_1(q^*(\theta, \eta), \theta) = p^*(\theta, \eta).$$

By employing either ideal signal, the *ex ante* uncertainty has in effect been eliminated *ex post* and we are right back to the case where there is no theoretical difference between price and quantity control modes.

It should be readily apparent that it is infeasible for the centre to transmit an entire schedule of ideal prices or quantities. A contingency message is a complicated, specialized contract which is expensive to draw up and hard to understand. The random variables are difficult to quantify. A problem of differentiated information or even of moral hazard may be involved since the exact value of θ will frequently be known only by the producer.[1] Even for the simplest case of just *one* firm, information from different sources must be processed, combined, and evaluated. By the time an ideal schedule was completed, another would be needed because meanwhile changes would have occurred.

In this paper the realistic issue of central control under uncertainty is considered to be the " second best " problem of finding for each producer the single price or quantity message which optimally regulates his actions. This is also the best way to focus sharply and directly on the essential difference between prices and quantities as planning instruments.

The issue of prices *vs.* quantities has to be a " second best " problem by its very nature simply because there is no good *a priori* reason for limiting attention to just these two particular signals. Even if stochastic contingency messages were eliminated on *ad hoc* grounds as being too complicated, there would still be no legitimate justification for not considering, say, an entire expected benefits schedule, or a " kinked " benefit function in the form of a two-tiered price system, or something else. The reason we specialize to price and quantity signals is that these are two *simple* messages, easily comprehended, traditionally employed, and frequently contrasted.[2]

The optimal quantity instrument under uncertainty is that target output $\hat{q}$ which maximizes expected benefits minus expected costs, so that

$$E[B(\hat{q}, \eta) - C(\hat{q}, \theta)] = \max_q E[B(q, \eta) - C(q, \theta)],$$

where $E[.]$ is the expected value operator. The solution $\hat{q}$ must satisfy the first order condition

$$E[B_1(\hat{q}, \eta)] = E[C_1(\hat{q}, \theta)]. \qquad \ldots(1)$$

When a price instrument p is announced, production will eventually be adjusted to the output level

$$q = h(p, \theta)$$

which maximizes profits given p and θ. Such a condition is expressed as

$$ph(p, \theta) - C(h(p, \theta), \theta) = \max_q pq - C(q, \theta),$$

implying

$$C_1(h(p, \theta), \theta) = p. \qquad \ldots(2)$$

[1] So that it may be inappropriate, for example, to tell him to produce less if costs are high unless a very sophisticated incentive scheme goes along with such a message. For an elaboration of some of these points see Arrow [1], pp. 321-322.

[2] There are real costs associated with using more complicated signals. At least implicitly, we are assuming that the magnitude of such costs is sufficiently large to make it uneconomical to consider messages other than prices or quantities. It would be nice to incorporate these costs explicitly into the model, but this is hard to do in any meaningful way.

If the planners are rational, they will choose that price instrument $\tilde{p}$ which maximizes the expected difference between benefits and costs given the reaction function $h(p, \theta)$:

$$E[B(h(\tilde{p}, \theta), \eta) - C(h(\tilde{p}, \theta), \theta)] = \max_{p} E[B(h(p, \theta), \eta) - C(h(p, \theta), \theta)].$$

The solution $\tilde{p}$ must obey the first order equation

$$E[B_1(h(\tilde{p}, \theta), \eta) . h_1(\tilde{p}, \theta)] = E[C_1(h(\tilde{p}, \theta), \theta) . h_1(\tilde{p}, \theta)],$$

which can be rewritten as

$$\tilde{p} = \frac{E[B_1(h(\tilde{p}, \theta), \eta) . h_1(\tilde{p}, \theta)]}{E[h_1(\tilde{p}, \theta)]}. \quad ...(3)$$

Corresponding to the optimal *ex ante* price $\tilde{p}$ is the *ex post* profit maximizing output $\tilde{q}$ expressed as a function of θ,

$$\tilde{q}(\theta) \equiv h(\tilde{p}, \theta). \quad ...(4)$$

In the presence of uncertainty, price and quantity instruments transmit central control in quite different ways. It is important to note that by choosing a specific mode for implementing an intended policy, the planners are at least temporarily locking themselves into certain consequences. The values of η and θ are at first unknown and only gradually, if at all, become recognized through their effects. After the quantity $\hat{q}$ is prescribed, producers will continue to generate that assigned level of output for some time even though in all likelihood

$$B_1(\hat{q}, \eta) \neq C_1(\hat{q}, \theta).$$

In the price mode on the other hand, $\tilde{q}(\theta)$ will be produced where except with negligible probability

$$B_1(\tilde{q}(\theta), \eta) \neq C_1(\tilde{q}(\theta), \theta).$$

Thus neither instrument yields an optimum *ex post*. The relevant question is which one comes closer under what circumstances.[1]

In an infinitely flexible control environment where the planners can continually adjust instruments to reflect current understanding of a fluid situation and producers instantaneously respond, the above considerations are irrelevant and the choice of control mode should be made to depend on other factors. Similar comments apply to a timeless *tâtonnement* milieu where iterations are costless, recontracting takes place after each round, and in effect nothing real is presumed to happen until all the uncertainty has been eliminated and an equilibrium is approached. In any less hypothetical world the consequences of an order given in a particular control mode have to be lived with for at least the time until revisions are made, and real losses will be incurred by selecting the wrong communication medium.

Note that the question usually asked whether it is better to control prices or quantities for *finding* a plan is conceptually distinct from the issue treated in this paper of which mode is superior for *implementing* a plan. The latter way of posing the problem strikes me as more relevant for most actual planning contexts—either because there is no significant informational difference between the two modes in the first place, or because a step in the *tâtonnement* planning game cannot meaningfully occur unless it is really implemented, or because no matter how many iterations have been carried out over time there are always spontaneously arising changes which damp out the significance of knowing past history. In the framework adopted here, the planners are at the decision node where as much information as is feasible to gather has already been obtained by one means or another and an operational plan must be decided on the basis of the available current knowledge.

[1] We remark in passing that the issue of whether it is better to stabilize uncertain demand and supply functions by pegging prices or quantities can also be put in the form of the problem analysed in this paper if benefits are associated with the consumers' surplus area under the demand curve and costs with the producers' surplus area under the supply curve.

III. PRICES *vs.* QUANTITIES

It is natural to define the *comparative advantage of prices over quantities* as

$$\Delta \equiv E[(B(\tilde{q}(\theta), \eta) - C(\tilde{q}(\theta), \theta)) - (B(\hat{q}, \eta) - C(\hat{q}, \theta))]. \qquad ...(5)$$

The loss function implicit in the definition of Δ is the expected difference in gains obtained under the two modes of control. Naturally there is no real distinction between working with Δ or with $-\Delta$ (the comparative advantage of quantities over prices).

The coefficient Δ is intended to be a measure of *comparative* or *relative* advantage only. It goes without saying that making a decision to use price or quantity control modes in a specific instance is more complicated than just consulting Δ. There are also going to be a host of practical considerations formally outside the scope of the present model. Although such external factors render Δ of limited value when isolated by itself, they do not necessarily diminish its conceptual significance. On the contrary, having an objective criterion of the *ceteris paribus* advantage of a control mode is very important because conceptually it can serve as a benchmark against which the cost of "non-economic" ingredients might be measured in reaching a final judgment about whether it would be better to employ prices or quantities as planning instruments in a given situation.

As it stands, the formulation of cost and benefit functions is so general that it hinders us from cleanly dissecting equation (5). To see clearly what Δ depends on we have to put more structure on the problem. It is possible to be somewhat less restrictive than we are going to be, but only at the great expense of clarity.

In what follows, the amount of uncertainty in marginal cost is taken as sufficiently small to justify a second order approximation of cost and benefit functions within the range of $\tilde{q}(\theta)$ as it varies around $\hat{q}$.[1] Let the symbol "$\cong$" denote an "accurate local approximation" in the sense of deriving from the assumption that cost and benefit functions are of the following quadratic form within an appropriate neighbourhood of $q = \hat{q}$:

$$C(q, \theta) \cong a(\theta) + (C' + \alpha(\theta))(q - \hat{q}) + \frac{C''}{2}(q - \hat{q})^2 \qquad ...(6)$$

$$B(q, \eta) \cong b(\eta) + (B' + \beta(\eta))(q - \hat{q}) + \frac{B''}{2}(q - \hat{q})^2. \qquad ...(7)$$

In the above equations $a(\theta)$, $\alpha(\theta)$, $b(\eta)$, $\beta(\eta)$ are stochastic functions and C', C'', B', B'' are fixed coefficients.

Without loss of generality, $\alpha(\theta)$ and $\beta(\eta)$ are standardized in (6), (7) so that their expected values are zero:

$$E[\alpha(\theta)] = E[\beta(\eta)] = 0. \qquad ...(8)$$

Since θ and η are independently distributed,

$$E[\alpha(\theta) \,.\, \beta(\eta)] = 0. \qquad ...(9)$$

Note that the stochastic functions

$$a(\theta) \cong C(\hat{q}, \theta)$$

$$b(\eta) \cong B(\hat{q}, \eta)$$

translate different values of θ and η into pure vertical shifts of the cost and benefit curves.

Differentiating (6) and (7) with respect to q,

$$C_1(q, \theta) \cong (C' + \alpha(\theta)) + C'' \,.\, (q - \hat{q}) \qquad ...(10)$$

$$B_1(q, \eta) \cong (B' + \beta(\eta)) + B'' \,.\, (q - \hat{q}). \qquad ...(11)$$

1 Such an approximation can be rigorously defended along the lines developed by Samuelson [8].

Employing the above equations and (8), the following interpretations are available for the fixed coefficients of (6), (7):

$$C' \stackrel{\circ}{=} E[C_1(\hat{q}, \theta)]$$

$$B' \stackrel{\circ}{=} E[B_1(\hat{q}, \eta)]$$

$$C'' \stackrel{\circ}{=} C_{11}(q, \theta)$$

$$B'' \stackrel{\circ}{=} B_{11}(q, \eta).$$

From (1),

$$B' = C'. \qquad ...(12)$$

It is apparent from (8) and (10) that stochastic changes in $\alpha(\theta)$ represent pure unbiased shifts of the marginal cost function. The variance of $\alpha(\theta)$ is precisely the mean square error in marginal cost

$$\sigma^2 \equiv E[(C_1(q, \theta) - E[C_1(q, \theta)])^2] \stackrel{\circ}{=} E[\alpha(\theta)^2]. \qquad ...(13)$$

Analogous comments hold for the marginal benefit function (11) where we have

$$E[(B_1(q, \eta) - E[B_1(q, \eta)])^2] = E[\beta(\eta)^2].$$

From (10) and (2),

$$h(p, \theta) \stackrel{\circ}{=} \hat{q} + \frac{p - C' - \alpha(\theta)}{C''} \qquad ...(14)$$

implying

$$h_1(p, \theta) \stackrel{\circ}{=} \frac{1}{C''}. \qquad ...(15)$$

Substituting from (15) into (3) and cancelling out C'' yields

$$\tilde{p} \stackrel{\circ}{=} E[B_1(h(\tilde{p}, \theta), \eta)]. \qquad ...(16)$$

Replacing q in (11) by the expression for $h(\tilde{p}, \theta)$ from (14) and plugging into (16), the following equation is obtained after using (8)

$$\tilde{p} \stackrel{\circ}{=} B' + \frac{B''}{C''}(\tilde{p} - C'). \qquad ...(17)$$

From (12) and the condition $B'' < 0 < C''$, (17) implies

$$\tilde{p} \stackrel{\circ}{=} C'. \qquad ...(18)$$

Combining (4), (14), and (18),

$$\tilde{q}(\theta) \stackrel{\circ}{=} \hat{q} - \frac{\alpha(\theta)}{C''}. \qquad ...(19)$$

Now alternately substitute $q = \hat{q}$ and $q = \tilde{q}(\theta)$ from (19) into (6) and (7). Then plugging the resulting values of (6), (7) into (5), using (8), (9), and collecting terms,

$$\Delta \stackrel{\circ}{=} \frac{\sigma^2 B''}{2C''^2} + \frac{\sigma^2}{2C''}. \qquad ...(20)$$

Expression (20) is the fundamental result of this paper.[1] The next section is devoted to examining it in detail.

[1] In the supply and demand context B'' is the slope of the (linear) demand curve, C'' is the slope of the (linear) supply curve, and σ^2 is the variance of vertical shifts in the supply curve.

IV. ANALYSING THE COEFFICIENT OF COMPARATIVE ADVANTAGE

Note that the uncertainty in benefits does not appear in (20).[1] To a second-order approximation it affects price and quantity modes *equally* adversely. On the other hand, Δ depends linearly on the mean square error in marginal cost. The *ceteris paribus* effect of increasing σ^2 is to magnify the expected loss from employing the planning instrument with comparative disadvantage. Conversely, as σ^2 shrinks to zero we move closer to the perfect certainty case where in theory the two control modes perform equally satisfactorily.

Clearly Δ depends critically on the curvature of cost and benefit functions around the optimal output level. The first thing to note is that the sign of Δ simply equals the sign of $C''+B''$. When the sum of the " other " considerations nets out to a zero bias toward either control mode, quantities are the preferred planning instrument if and only if benefits have more curvature than costs.

Normally we would want to know the magnitude of Δ and what it depends on, as well as the sign. To strengthen our intuitive feeling for the meaning of formula (20), we turn first to some extreme cases where there is a strong comparative advantage to one control mode over the other. In this connection it is important to bear in mind that when we talk about " large " or " small " values of B'', C'', or σ^2, we are only speaking in a relative sense. The absolute measure of any variable appearing in (20) does not really mean much alone since it is arbitrarily pegged by selecting the units in which output is reckoned.

The coefficient Δ is negative and large as either the benefit function is more sharply curved or the cost function is closer to being linear. Using a price control mode in such situations could have detrimental consequences. When marginal costs are nearly flat, the smallest miscalculation or change results in either much more or much less than the desired quantity. On the other hand, if benefits are almost kinked at the optimum level of output, there is a high degree of risk aversion and the centre cannot afford being even slightly off the mark. In both cases the quantity mode scores a lot of points because a high premium is put on the rigid output controllability which only it can provide under uncertainty.

From (20), the price mode looks relatively more attractive when the benefit function is closer to being linear. In such a situation it would be foolish to name quantities. Since the marginal social benefit is approximately constant in some range, a superior policy is to name it as a price and let the producers find the optimal output level themselves, after eliminating the uncertainty from costs.

At a point where the cost function is highly curved, Δ becomes nearly zero. If marginal costs are very steeply rising around the optimum, as with fixed capacity, there is not much difference between controlling by price or quantity instruments because the resulting output will be almost the same with either mode. In such a situation, as with the case $\sigma^2 = 0$, " non-economic " factors should play the decisive role in determining which system of control to impose.

It is difficult to refrain from noticing that although there are plenty of instances where

[1] This is because the *expected* benefit function (see equation (7)) does not depend on the variance of marginal benefits so long as costs and benefits are independently distributed. If they are *not*, so that

$$\sigma_{bc}^2 \equiv E[\{C_1(q, \theta)-E[C_1(q, \theta)]\}.\{B_1(q, \eta)-E[B_1(q, \eta)]\}] = E[\alpha(\theta).\beta(\eta)] \neq 0,$$

(20) must be replaced by: $\Delta \simeq \frac{\sigma^2 B''}{2C''^2} + \frac{1}{2C''}(\sigma^2 - 2\sigma_{bc}^2)$. The sole effect of having costs and benefits correlated with each other is embodied in the term σ_{bc}^2. When marginal costs are positively correlated with marginal benefits, the *ceteris paribus* comparative advantage of the quantity mode is increased. If prices are used as a control mode, the producer will tend to cut back output for high marginal costs. But with σ_{bc}^2 positive, this is the very same time that marginal benefits tend to be high, so that a cutback may not really be in order. In such situations the quantity mode has better properties as a stabilizer, other things being equal. The story is the other way around when σ_{bc}^2 is negative. In that case high marginal costs are associated with low marginal benefits, so that the price mode (which decreases output for high marginal costs) tends to be a better mode of control other things being equal.

the price mode has a good solid comparative advantage (because $-B''$ is small), in some sense it looks as if prices can be a *disastrous* choice of instrument far more often than quantities can. Using (20), $\Delta \to -\infty$ if either $B'' \to -\infty$ or $C'' \to 0$ (or both). The only way $\Delta \to +\infty$ is under the thin set of circumstances where simultaneously $C'' \to 0$, $B'' \to 0$, and $C'' > -B''$. In a world where C'' and B'' are themselves imperfectly known it seems hard to avoid the impression that there will be many circumstances where the more conservative quantity mode will be preferred by planners because it is better for avoiding very bad planning mistakes.[1]

Having seen how C'' and B'' play an essential role in determining Δ, it may be useful to check out a few of the principal situations where we might expect to encounter cost and benefit functions of one curvature or another. We start with costs.

Contemporary economic theory has tended to blur the distinction between the traditional marginalist way of treating production theory with smoothly differentiable production functions and the activity analysis approach with its limited number of alternative production processes. For many theoretical purposes convexity of the underlying technology is really the fundamental property.

However, there are very different implications for the efficacy of price and quantity control modes between a situation described by classically smooth Marshallian cost curves and one characterized by piecewise linear cost functions with a limited number of kinks. In the latter case, the quantity mode tends to have a relative advantage since $\Delta = -\infty$ on the flats and $\Delta = 0$ at the elbows. Of course it is impossible to use a price to control an output at all unless some hidden fixed factors take the flatness out of the average cost curve. Even then, Δ will be positive only if there are enough alternative techniques available to make the cost function have more (finite difference) curvature than the benefit function in the neighbourhood of an optimal policy.

What determines the benefit function for a commodity is contingent in the first place on whether the commodity is a final or intermediate good. The benefit of a final good is essentially the utility which arises out of consuming the good. It could be highly curved at the optimum output level if tastes happen to be kinked at certain critical points. The amount of pollution which makes a river just unfit for swimming could be a point where the marginal benefits of an extra unit of output change very rapidly. Another might be the level of defence which just neutralizes an opponent's offence or the level of offence which just overcomes a given defence. There are many examples which arise in emergencies or natural calamities. Our intuitive feeling, which is confirmed by the formal analysis, is that it doesn't pay to " fool around " with prices in such situations.

For intermediate goods, the shape of the benefit function will depend among other things on the degree of substitutability in use of this commodity with other resources available in the production organization and upon the possibilities for importing this

[1] This idea could be formalized as follows. Consider two generalizations of formulae (6) and (7):

$$C(q, \theta) \cong a(\theta) + (C' + \alpha(\theta))(q - \hat{q}) + \frac{C''}{2f(\theta)}(q - \hat{q})^2$$

$$B(q, \eta) \cong b(\eta) + (B' + \beta(\eta))(q - \hat{q}) + \frac{B''g(\eta)}{2}(q - \hat{q})^2.$$

The only difference with (6), (7) is that now $1/C_{11}(q, \theta)$ and $B_{11}(q, \eta)$ are allowed to be uncertain. The change in the profit maximizing output response per unit price change is now stochastic, $h_1(p, \theta) = f(\theta)/C''$. Without loss of generality we set

$$E[f(\theta)] = E[g(\eta)] = 1.$$

Note that increasing the variance of $f(g)$ is a mean preserving spread of C_{11} (B_{11}). Suppose for simplicity that f and α are independent of each other. Then we can derive the appropriate generalization of (20) as

$$\Delta \cong \frac{B''\sigma^2(1+\delta^2)}{2C''^2} + \frac{\sigma^2}{2C''},$$

where $\delta^2 \equiv E[\{f(\theta) - E[f(\theta)]\}^2]$ is the variance of $f(\theta)$. The above formula can be interpreted as saying that other things being equal, greater uncertainty in $1/C_{11}(q, \theta)$ increases the comparative advantage of the quantity mode.

commodity from outside the organization. These things in turn are very much dependent on the planning time horizon. In the long run the benefit function probably becomes flatter because more possibilities for substitution are available, including perhaps importing. Take for example the most extreme degree of complete " openness " where any amount of the commodity can be instantaneously and effortlessly bought (and sold) outside the production organization at a fixed price. The relevant benefit function is of course just a straight line whose slope is the outside price.

There is, it seems to me, a rather fundamental reason to believe that quantities are better signals for situations demanding a high degree of coordination. A classical example would be the short run production planning of intermediate industrial materials. Within a large production organization, be it the General Motors Corporation or the Soviet industrial sector as a whole, the need for balancing the output of any intermediate commodity whose production is relatively specialized to this organization and which cannot be effortlessly and instantaneously imported from or exported to a perfectly competitive outside world puts a kink in the benefit function. If it turns out that production of ball bearings of a certain specialized kind (plus reserves) falls short of anticipated internal consumption, far more than the value of the unproduced bearings can be lost. Factors of production and materials that were destined to be combined with the ball bearings and with commodities containing them in higher stages of production must stand idle and are prevented from adding value all along the line. If on the other hand more bearings are produced than were contemplated being consumed, the excess cannot be used immediately and will only go into storage to lose implicit interest over time. Such short run rigidity is essentially due to the limited substitutability, fixed coefficients nature of a technology based on machinery.[1] Other things being equal, the asymmetry between the effects of overproducing and underproducing are more pronounced the further removed from final use is the commodity and the more difficult it is to substitute alternative slack resources or to quickly replenish supplies by emergency imports. The resulting strong curvature in benefits around the planned consumption levels of intermediate materials tends to create a very high comparative advantage for quantity instruments. If this is combined with a cost function that is nearly linear in the relevant range, the advantage of the quantity mode is doubly compounded.[2]

V. MANY PRODUCTION UNITS

Consider the same model previously developed except that now instead of being a single good, $q = (q_1, ..., q_n)$ is an n-vector of commodites. The various components of q might represent physically distinct commodities or they could denote amounts of the same commodity produced by different production units. Benefits are $B(q, \eta)$ and the cost of producing the ith good is $c^i(q_i, \theta_i)$. As before, for each i the two random variables η and θ_i are distributed independently of each other.

Suppose the issue of control is phrased as choosing either the quantities $\{\hat{q}_i\}$ which maximize

$$E\left[B(q,.\eta)-\sum_1^n c^i(q_i, \theta_i)\right],$$

[1] The existence of buffer stocks changes the point at which the kink occurs, but does not remove it. For a more detailed treatment of this entire topic, see Manove [6].

[2] Note that in the context of an autarchic planned economy, such pessimistic conclusions about the feasibility of using Lange-Lerner price signals to control short run output do not carry over to, say, agriculture. The argument just given for a kinked benefit function would not at all pertain to a food crop, which goes more or less directly into final demand. In addition, the cost function for producing a given agricultural commodity ought to be much closer to the classical smooth variety than to the linear programming type with just a few kinks.

or the prices $\{\tilde{p}_i\}$ which maximize

$$E[B(h(p, \theta), \eta) - \Sigma c^i(h_i(p_i, \theta_i), \theta_i)],$$

where $\{h_i(p_i, \theta_i)\}$ are defined analogously to (2).

Naturally the coefficient of comparative advantage is now defined as

$$\Delta_n \equiv E\left[\left\{B\left(\tilde{q}(\theta), \eta\right) - \sum_1^n c^i(\tilde{q}_i(\theta_i), \theta_i)\right\} - \left\{B(\hat{q}, \eta) - \sum_1^n c^i(\hat{q}_i, \theta_i)\right\}\right].$$

Assuming locally quadratic costs and benefits, it is a straightforward generalization of what was done in Section III to derive the analogue of expression (20),

$$\Delta_n \simeq \sum_{i=1}^n \sum_{j=1}^n \frac{B_{ij}\sigma_{ij}^2}{2c_{11}^i c_{11}^j} + \sum_{i=1}^n \frac{\sigma_{ii}^2}{2c_{11}^i}, \qquad \text{...(21)}$$

where

$$\sigma_{ij}^2 \simeq E[\{c_1^i(q_i, \theta_i) - E[c_1^i(q_i, \theta_i)]\}\{c_1^j(q_j, \theta_j) - E[c_1^j(q_j, \theta_j)]\}]. \qquad \text{...(22)}$$

To correct for the pure effect of n on Δ_n, it is more suitable to work with the transformed cost functions

$$C^i(x_i, \theta_i) \equiv nc^i(x_i/n, \theta_i). \qquad \text{...(23)}$$

The meaning of C^i is most readily interpreted for the situation where n different units are producing the same commodity or a close substitute with similar cost functions. Then C^i is what total costs would be as a function of total output if each production unit were an identical replica of the ith unit. When " other things being equal " n is changed, it is more appropriate to think of C^i being held constant rather than c^i.

With C^i defined by (23), we have

$$C_1^i = c_1^i \qquad \text{...(24)}$$

$$C_{11}^i = \frac{c_{11}^i}{n}. \qquad \text{...(25)}$$

Relation (24) means that in the quadratic case the coefficients of the marginal cost variance-covariance matrix for the $\{C_1^i\}$ are the same as those given by (22) for the $\{c_1^i\}$. Substituting (25) into (21),

$$\Delta_n \simeq \frac{1}{n^2} \sum_{i=1}^n \sum_{j=1}^n \frac{B_{ij}\sigma_{ij}^2}{2C_{11}^i C_{11}^j} + \frac{1}{n} \sum_{i=1}^n \frac{\sigma_{ii}^2}{2C_{11}^i}. \qquad \text{...(26)}$$

The above formula shows that in effect the original expression for Δ holds *on the average* for Δ_n when there is more than one producer. Naturally the generalization (26) is more complicated, but the interpretation of it is basically similar to the diagnosis of (20) which was just given in the previous section.

There is, however, a fundamental distinction between having one and many producers which is concealed in formula (26). With some degree of independence among the distributions of individual marginal costs, less weight will be put on the first summation term of (26). Other things being equal, in situations with more rather than fewer independent units producing outputs which substitute for each other in yielding benefits, there is a correspondingly greater relative advantage to the price mode of control. Although this point has general validity, it can be most transparently seen in the special regularized case of one good being produced by many micro-units with symmetrical cost functions. In such a case

$$B_{ij} = B'' \qquad \text{...(27.i)}$$

$$C_{11} = C'' \qquad \text{...(27.ii)}$$

$$\sigma_{ii}^2 = \sigma^2 \qquad \text{...(27.iii)}$$

$$\sigma_{ij}^2 = \rho\sigma^2, \quad i \neq j, \quad -1 \leq \rho \leq 1. \qquad \text{...(27.iv)}$$

The coefficient ρ is a measure of the correlation between marginal costs of separate production units. If all units are pretty much alike and are using a similar technology, ρ is likely to be close to unity. If the cost functions of different units are more or less independent of each other, ρ should be nearly zero. While in theory the correlation coefficient can vary between plus and minus unity, for most situations of practical interest the marginal costs of two different production units will have a non-negative cross correlation.

Using (27), (26) can be rewritten as

$$\Delta_n \simeq \rho\left(\frac{B''\sigma^2}{2C''^2} + \frac{\sigma^2}{2C''}\right) + (1-\rho)\left(\frac{1}{n}\frac{B''\sigma^2}{2C''^2} + \frac{\sigma^2}{2C''}\right). \qquad \text{...(28)}$$

If the marginal costs of each identical micro-unit are perfectly correlated with each other so that $\rho = 1$, it is as if there is but a single producer and we are exactly back to the original formula (20). With $n > 1$, as ρ decreases, Δ_n goes up. A *ceteris paribus* move from dependent toward independent costs increases the comparative advantage of prices, an effect which is more pronounced as the number of production units is larger. If there are three distinctly different types of sulphur dioxide emitters with independent technologies instead of one large pollution source yielding the same aggregate effect, a relatively stronger case exists for using prices to regulate output.

When it is desired to control different units producing an identical commodity by setting prices, only a single price need be named as an instrument. The price mode therefore possesses the *ceteris paribus* advantage that output is being produced efficiently *ex post*. With prices as instruments

$$c_1^i(\tilde{q}_i, \theta_i) = c_1^j(\tilde{q}_j, \theta_j) = \tilde{p},$$

whereas with quantities

$$c_1^i(\hat{q}_i, \theta_i) \neq c_1^j(\hat{q}_j, \theta_j)$$

except on a set of negligible probability.

Using prices thus enables the centre to automatically screen out the high cost producers, encouraging them to produce less and the low cost units more. This predominance in efficiency makes the comparative advantage of the price mode go up as the number of independent production units becomes larger, other things being equal. The precise statement of such a proposition would depend on exactly what was held equal as n was increased—the variance of *individual* costs or the overall variance of *total* costs. For simplicity consider the case of completely independent marginal costs, $\rho = 0$. Then (28) becomes

$$\Delta_n \simeq \frac{1}{n}\frac{B''\sigma^2(n)}{2C''^2} + \frac{\sigma^2(n)}{2C''}, \qquad \text{...(29)}$$

where $\sigma^2(n)$ is implicitly some (given) function of n. If the " other thing " being equal is the constant variance of marginal costs for each individual producing unit, then $\sigma^2(n) \equiv \sigma^2$. If the variance of total costs is held constant as n varies, $\sigma^2(n) \equiv n\sigma^2$. Either way Δ_n in (29) increases monotonically with n and eventually becomes positive.

It is important to note that such *ceteris paribus* efficiency advantages of the price mode as we have been considering for large n are by no means enough to guarantee that Δ_n will be positive in a particular situation for any *given n*. True, what aggregate output is forthcoming under the price mode will be produced at least total cost. But it might be the wrong overall output level to start with. If the $\{-B_{ij}\}$ are sufficiently large or the $\{C_{11}^i\}$ sufficiently small, it may be advantageous to enjoy greater control over total output by setting individual quotas, even after taking account (as our formula for Δ_n does) of the losses incurred by the *ex post* productive inefficiency of such a procedure.[1]

Returning to the general case with which this section began, we note that the basic difference between benefits and costs becomes somewhat more transparent in the n commodity vector formulation. Only the centre knows benefits. Even if it could be done it would not help to transmit $B(.)$ to individual production units because benefits are typically a non-separable function of *all* the units' outputs, whereas a particular unit has control only over its *own* output. In any well formulated mode of decentralized control, the objective function to be maximized by a given unit must depend in some well-defined way on *its* decisions alone. For the purposes of our formulation B need not be a benefit and the $\{c^i\}$ need not be costs in the usual sense, although in many contexts this is the most natural interpretation. The crucial distinction is that B is in principle knowable only by the centre, whereas c^i is best known by firm i.[2]

When uncertainties in individual costs are unrelated so that the random variables θ_i and θ_j are independently distributed, the decision to use a price or quantity instrument to control q_i alone is decentralizable. Suppose it has already been resolved by one means or another whether to use price or quantity instruments to control q_j for each $j \neq i$. To a quadratic approximation, the comparative advantage of prices over quantities for commodity i is

$$\Delta^i \cong \frac{\sigma_{ii}^2 B_{ii}}{2c_{11}^{i2}} + \frac{\sigma_{ii}^2}{2c_{11}^i}, \qquad \ldots(30)$$

which is exactly the formula (20) for this particular case.

In some situations, " mixed " price-quantity modes may give the best results. As a specific example, suppose that q_1 is the catch of a certain fish from a large lake and q_2 from a small but prolific pond. Let q_1 be produced with relatively flat average costs but q_2 have a cost function which is curved at the optimum somewhat more than the benefit function. The optimal policy according to (30) will be to name a quota for q_1 and a price for q_2.

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[1] An even better procedure from a theoretical point of view in the case where an identical output is produced by many firms would be to fix *total* output by command and subdivide it by a price mechanism. This kind of solution is proposed by Dales [2] who would set up a market in " pollution rights ", the fixed supply of which is regulated by the government. In effect, such an approach aggregates the individual cost functions, and we are right back to a single cost function. Note that a basic question would still remain: is it better to fix the total amount by a quantity or price control mode?

[2] An interesting application of the ideas of this section is provided by the problem of choosing a control mode for best distributing a deficit commodity in fixed supply (say gasoline). In this case what we have been calling an individual cost function, $c^i(q_i, \theta_i)$, would really be the negative of a user's benefit function (as measured by the area under his demand curve). Our B function (of total demand) would just reflect the opportunity loss of having a surplus or shortage of the implied amount when only a fixed supply is available. All the considerations of this section would apply in determining the coefficient of comparative advantage. Accurately characterizing the B function seems especially difficult in the present context. If the commodity can be bought from or sold to the outside world, the B function would just embody the terms of this opportunity (in particular, it would be flat if any amount of the commodity could be bought or sold at some fixed price). Under autonomy, the shape of the B function would depend on what is done in a surplus or deficit situation. With a surplus (from naming too high a price), it would depend on the value to future allocation possibilities of the excess supply, relative to what welfare was lost at the present

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time from having demand less than supply. With a deficit (from naming too low a price), the loss of welfare hinges on how shortages are actually distributed among consumers. If shortages result in some people doing completely without the product, the overall welfare losses may be very great and $|B''|$ could be large. If there is some inherent reason to believe that shortages will automatically be evenly distributed, then $|B''|$ may not be so big. In addition to redistribution losses, there will always be waiting time losses in a shortage. Finally, note that if the amount of the fixed supply is known, a superior policy to naming prices or quantities is to distribute ration tickets (instead of quantities), allowing them to be resold at a competitively determined market price.

This is Exhibit D referred to in the Affidavit of JUNE PARKER sworn before me this 11 day of DECEMBER A.D. 2018 2015

A Commissioner for taking Affidavits within British Columbia

PNAS

Economic aspects of global warming in a post-Copenhagen environment

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The science of global warming has reached a consensus on the high likelihood of substantial warming over the coming century. Nations have taken only limited steps to reduce greenhouse gas emissions since the first agreement in Kyoto in 1997, and little progress was made at the Copenhagen meeting in December 2009. The present study examines alternative outcomes for emissions, climate change, and damages under different policy scenarios. It uses an updated version of the regional integrated model of climate and the economy (RICE model). Recent projections suggest that substantial future warming will occur if no abatement policies are implemented. The model also calculates the path of carbon prices necessary to keep the increase in global mean temperature to 2 °C or less in an efficient manner. The carbon price for 2010 associated with that goal is estimated to be $59 per ton (at 2005 prices), compared with an effective global average price today of around $5 per ton. However, it is unlikely that the Copenhagen temperature goal will be attained even if countries meet their ambitious stated objectives under the Copenhagen Accord.

abatement strategies | climate change | Copenhagen Accord | economic growth | integrated assessment models

The world is far along in what Roger Revelle and Hans Suess called "our great geophysical experiment" (1). The failure of nations in Copenhagen in December 2009 to reach a concrete agreement to extend and broaden the Kyoto Protocol raises the prospect that attempts to limit atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs), with the resulting global temperature increases, may prove politically difficult. This study reports improved estimates of the likely trajectories of global output, GHG emissions, climate change, and damages in the coming decades.

Climatologists and other scientists have warned for more than half a century that the accumulation of CO_2 and other GHGs in the atmosphere is leading to global warming and other significant climatic, ecological, and societal changes. However, the economic, political, and institutional issues involved in limiting GHG emissions have only begun to be considered over the past 2 decades. The difficulty is that reducing emissions is an extreme "global public good," meaning that no single nation can capture for itself a substantial part of the benefits from its own emission reductions (2). The intellectual challenge is daunting, raising formidable issues of data, modeling, uncertainty, international coordination, and institutional design. In addition, the economic stakes in climate-change policy are huge.

What are the stakes if nations fail to reach meaningful climate-change agreements? In other words, what are the climatic and economic consequences of uncontrolled emissions of GHGs over the coming decades? These questions become particularly salient, given the apparent difficulties of reaching a binding and effective international agreement. Surprisingly, the impressive work of scientific bodies such as the Intergovernmental Panel on Climate Change (IPCC) does not address the likely trajectory of uncontrolled emissions, either in the past two rounds of assessments or prospectively in the coming fifth round. The present study attempts to explain the issues and provide some tentative answers.

The Copenhagen Accord

The agreed framework for all international climate-change deliberations is the United Nations Framework Convention on Climate Change, ratified in 1994. That document stated, "The ultimate objective…is to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (3). The Framework Convention was implemented in the Kyoto Protocol in 1997, in which both high-income countries and countries in transition from socialism agreed to binding emissions limits for the 2008–2012 period. However, the reality of global warming policy has lagged far behind scientific prescriptions. This is seen in the attrition in covered emissions. The original Kyoto Protocol covered ≈66% of 1990 industrial CO_2 emissions. However, with the failure of the United States to ratify the agreement and the decline in the relative emissions of rich countries, the Kyoto Protocol currently covers only ≈27% of global emissions.

The 2009 Copenhagen meeting was designed to negotiate a successor agreement for the post-Kyoto period. Because of deep divisions about costs and the distribution of emissions reductions, the meeting concluded without a binding agreement. However, it did lead to an agreement known as the "Copenhagen Accord" (4). The accord adopts a target of limiting the increase in global mean temperature, "recognizing the scientific view that the increase…should be below 2 degrees Celsius." Those looking for a silver lining behind the cloudy outcome have pointed to the fact that developing countries joined the accord. A close look reveals, however, that developing countries committed themselves to very little. They agreed to "communicate" their "nationally appropriate mitigation actions seeking international support efforts," but no binding targets for developing countries were set. By mid-2010, most countries have communicated their plans.

The reality behind the accord is not encouraging. To begin with, even if the high-income countries fulfilled their commitments, these would probably not achieve anything close to the 2 °C target, as is shown below. Meanwhile, progress on reaching a more binding agreement has been glacial at best. At present, a global agreement is waiting for the United States to take credible legislated steps. Continued delay in adoption of climate-change policies by the United States may lead to a domino effect in which other countries follow the US inaction.

Given these developments, it is useful to review the prospects for climate change and the economic implications, both for the case in which controls are implemented as envisioned by the Copenhagen Accord and for the case in which the present stalemate continues. This report presents the results of an updated version of the regional integrated model of climate and the economy (RICE model), denoted the RICE-2010 model. The model is a regionalized, dynamic, integrated assessment model of

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ECONOMIC SCIENCES

the global economy and climate change that incorporates an end-to-end treatment of economic growth, emissions, the carbon cycle, climate change, damages, and emissions controls. The model allows the computation of internally consistent projections of the effects of alternative policy regimes. I begin with a succinct description of the model.*

The RICE-2010 Model

The RICE model views climate change in the framework of economic growth theory. In a standard neoclassical optimal growth model known as the Ramsey model, society invests in capital goods, thereby reducing consumption today so as to increase consumption in the future (5, 6). The RICE model modifies the Ramsey model to include climate investments. The capital stock of the conventional model is extended to include investments in the environment ("natural capital"). Emissions reductions in the extended model are analogous to capital investments in the mainstream model. That is, we can view concentrations of GHGs as "negative natural capital" and emissions reductions as lowering the quantity of that negative capital. Emissions reductions lower consumption today but, by preventing economically harmful climate change, increase consumption possibilities in the future.

The model divides the world into 12 regions. Some are large countries such as the United States or China; others are large multicountry regions such as the European Union or Latin America. Each region is assumed to have a well-defined set of preferences, represented by a social welfare function, and to optimize its consumption, GHG policies, and investment over time. The social welfare function is increasing in the per capita consumption of each generation, with diminishing marginal utility of consumption. The importance of a generation's per capita consumption depends on its relative size. The relative importance of different generations is measured using a pure rate of time preference, and the curvature of the utility function is given by the elasticity of the marginal utility of consumption. These parameters are calibrated to ensure that the real interest rate in the model is close to the average real interest rate and the average real return on capital in real-world markets (7, 8).

The model contains both a traditional economic sector like that found in many economic models and geophysical relationships designed for climate-change modeling.

Economic Sectors. Each region is assumed to produce a single commodity, which can be used for consumption, investment, or emissions reductions. Each region is endowed with an initial stock of capital and labor and with an initial and region-specific level of technology. Population data are from the United Nations, updated with more recent estimates through 2009, with projections using the United Nations' estimates to 2300 (9). Output is measured as standard gross domestic product (GDP) in constant prices, and the GDPs of different countries are converted into 2005 US international prices using purchasing-power-parity exchange rates. Output data through 2009 are from the World Bank and the International Monetary Fund (IMF), with projections to 2014 from the IMF (10, 11). CO_2 emissions data are from the US Energy Information Administration and Carbon Dioxide Information Analysis Center and are available through 2008.

Population growth and technological change are exogenous in the baseline model, whereas capital accumulation is determined by optimizing the flow of consumption over time. Output is determined using a Cobb–Douglas production function with capital, labor, and carbon-energy as inputs. Technological change takes two forms: economy-wide technological change and carbon-energy-saving technological change. The former is Hicks-neutral, and the latter is modeled as reducing the ratio of CO_2 emissions to carbon-energy inputs. Technological change is projected for a frontier region (the United States), and other countries are assumed to converge partway to the frontier. For convenience, both carbon-energy inputs and industrial emissions are measured in units of carbon weight (7, 12). Economic growth rates for the different regions are provided in *SI Appendix*, Table S1.

I calibrate the energy-related parameters using data on historical GDP and CO_2 emissions for the period 1960–2008. The model uses a cost function for CO_2 emissions reductions that is drawn from more detailed models at the national and regional levels from the IPCC Fourth Assessment Report (13) and the Energy Modeling Forum 22 report (14). *SI Appendix*, Fig. S1 shows historical rates of decarbonization. Additionally, there is a backstop technology that can replace all carbon fuels at a relatively high price ($1,260 per ton of carbon for the emissions-weighted global average), declining over time, drawn from IPCC surveys and other sources (15). It is assumed that the backstop technology becomes increasingly competitive with carbon fuels after 2250, such that emissions decline rapidly thereafter. The supply curve allows for limited, albeit very large, long-run supplies of carbon fuels. In the optimal-growth framework, energy resources are efficiently allocated across time, which implies that low-cost carbon resources have scarcity prices (called "Hotelling rents") and that carbon-energy prices rise over time (16).

Solution of a multicountry general economic equilibrium model poses major modeling issues. I have used a modification of the Negishi procedure introduced by Nordhaus and Yang (17). The modification is that the welfare weights are set to equalize the period-by-period marginal utilities using the weighted average marginal utility, where each region's weights are the regions' shares of the global capital stock in a given period.

Geophysical Sectors. The geophysical part of the model contains a number of relationships that link together the different factors affecting climate change. These include simplified relationships to capture CO_2 emissions, a carbon cycle, radiative forcings, a simple climate model, and regional climate-damage relationships. Each of these is drawn from more complex models and can be regarded as models of very simplified structure.

Emissions include all GHG emissions, although they comprise primarily CO_2 emissions. Endogenous emissions in the RICE-2010 model are limited to industrial CO_2. Chlorofluorocarbons are now outside the climate-change protocols. Other contributions to global warming are taken as exogenous. These include CO_2 emissions from land-use changes, non-CO_2 GHGs, and sulfate aerosols (18, 19).

The model uses a three-reservoir model calibrated to existing carbon-cycle models to calculate the carbon cycle. Climate change is represented by global mean surface temperature, and the relationship uses the results of the Fourth Assessment Report of the IPCC to estimate the lag structure and the equilibrium, which are calibrated to include the decreasing uptake of carbon with rising temperature (19).The RICE-2010 model contains a module with calculations of sea-level rise (SLR) associated with different temperature trajectories. The current version assumes that the equilibrium temperature-sensitivity coefficient is 3.2 °C per CO_2 doubling. The model has also been checked by comparing results with those of the 2009 version of the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC).

Understanding the market and nonmarket impacts of climate change continues to be the thorniest issue in climate-change economics. The RICE-2010 model provides a revised set of damage estimates based on a recent review of the literature (20, 21). Damages are a function of temperature, SLR, and CO_2 concentrations and are region-specific. To give an idea of the estimated

*The equations of the model, along with key assumptions, are available in *SI Appendix*. The model is also available as an Excel spreadsheet downloadable from the author's website (http://www.econ.yale.edu/~nordhaus/homepage/homepage.htm). The results reported here are based on the RICE model version of April 25, 2010.

damages in the uncontrolled (baseline) case, those damages in 2095 are $12 trillion, or 2.8% of global output, for a global temperature increase of 3.4 °C above 1900 levels.

There have been many recent studies concerned with abrupt and catastrophic climate change (22–24). Estimates for the economic costs of such scenarios are included in the damage estimates in the RICE model, but the model does not build in a precise tipping point at a given temperature increase, because such a tipping point has not been reliably determined.

Policy Scenarios

I examine the economic and climate trajectories associated with five different international policy approaches:

(*i*) Baseline: No climate-change policies are adopted.
(*ii*) Optimal: Climate-change policies maximize economic welfare, with full participation by all nations starting in 2010 and without climatic constraints.
(*iii*) Temperature-limited: The optimal policies are undertaken subject to a further constraint that global temperature does exceed 2 °C above the 1900 average.
(*iv*) Copenhagen Accord: High-income countries implement deep emissions reductions similar to those included in the current US proposals, with developing countries following in the next 2 to 5 decades.
(*v*) Copenhagen Accord with only rich countries: High-income countries implement deep reductions as in scenario 4, but developing countries do not participate until the 22nd century.

The baseline can be interpreted as complete inaction and stalemate on climate policies. The "optimal" scenario assumes the most efficient climate-change policies; in this context, efficiency involves a balancing of the costs of abatement and the benefits of reduced climate damages. Although unrealistic, this scenario provides an efficiency benchmark against which other policies can be measured. The "temperature-limited" scenario is a variant of the optimal scenario that builds in a precautionary constraint that a specific temperature increase is not exceeded. The Copenhagen Accord scenario assumes that the announced emissions-reduction policies for high-income countries for the near term are implemented. It then extends these to other high-income countries to parallel the United States-proposed reductions. Developing countries are assumed to follow within a few decades. *SI Appendix*, Table S2 shows the base and commitment years for different regions. The fifth scenario is the same as the Copenhagen Accord scenario, but developing countries do not participate until well into the 22nd century. For this scenario, the high-income participants are the United States, the European Union, Japan, Russia, and a group of other high-income countries.

Major Results

The Major Cases. The results presented here should be viewed as only suggestive and illustrative. They come from a single model and modeling perspective, and most of the relationships are subject to large uncertainties.

Figs. 1–4 report the main results. Further results are available in *SI Appendix*, Table S3. Fig. 1 shows global CO_2 emissions under each of the five policy scenarios. Unrestrained emissions are estimated to grow very rapidly. Emissions under the optimal and temperature-limited scenarios are essentially flat for the next 2 to 6 decades and then decline. The optimal path imposes a cut in global emissions of 50% from 2005 in 100 y, and the temperature-limited path prescribes zero emissions at about 2075.

Atmospheric concentrations of CO_2 rise sharply under the baseline path, reaching 793 ppm by 2100 (Fig. 2 and *SI Appendix*, Table S3 presents the numerical data). The optimal and temperature-limited paths show some slight continuation in the rise of concentrations from current levels, peaking between 500 and 600 ppm. (Note that these refer to CO_2 concentrations rather than to CO_2-equivalent concentrations.) Radiative forcings (not shown) peak at 4.4 W/m^2 in the optimal path and at 3.2 W/m^2 in the temperature-limited path. These forcings include those from other GHGs as well as estimates of other anthropogenic forcings, such as from sulfates.

Global temperature projections, shown in Fig. 3, rise sharply under the baseline, with increases of 3.5 °C in 2100 and 5.7 °C in 2200 and a peak (not shown) at 6.7 °C, all relative to 1900. The optimal and temperature-limited paths rise in the early 21st century because of the momentum of past emissions. They then bend downward as emissions are reduced, peaking at 2 °C (obviously) for the temperature-limited path and at 3.0 °C for the optimal path. Two important results are that the optimal path has a relatively low maximum temperature and the temperature increase for this path averaged over 2100–2300 is 2.7 °C.

Perhaps the most important outputs of integrated economic models of climate change are the near-term "carbon prices." This is a concept that measures the marginal costs of reductions of emissions of GHGs. In a market environment, such as a cap-and-trade regime, the carbon prices would be the trading price of

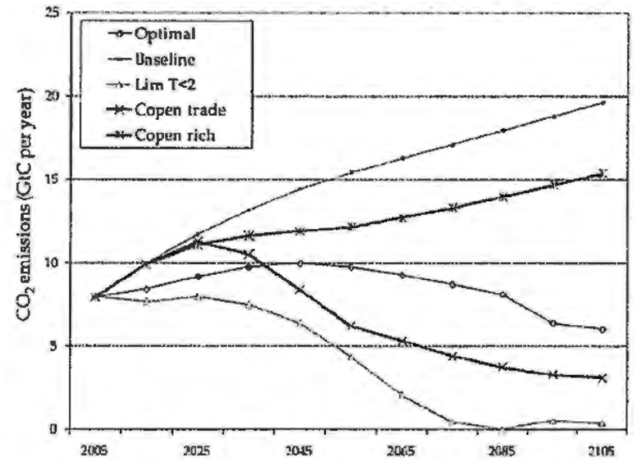

Fig. 1. Projected emissions of CO_2 under alternative policies. Copen, Copenhagen.

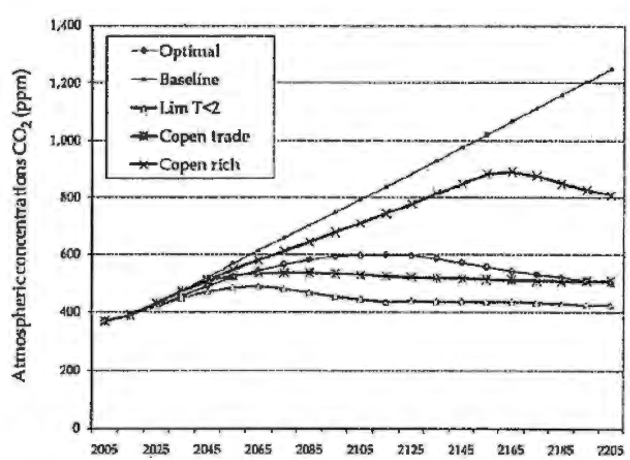

Fig. 2. Atmospheric concentrations of CO_2 under alternative policies. Copen, Copenhagen.

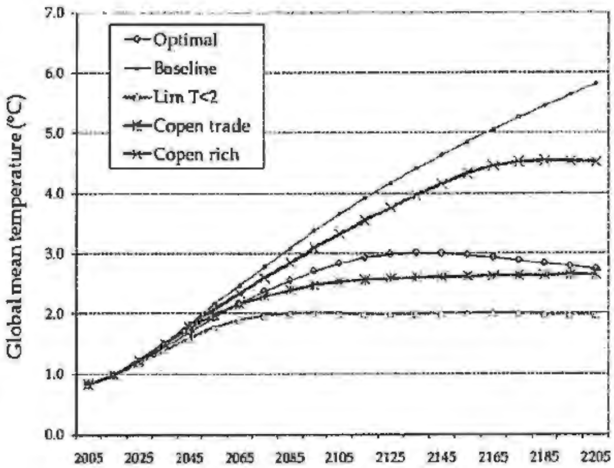

Fig. 3. Global temperature increase (°C from 1900) under alternative policies. Copen, Copenhagen.

carbon emission permits. We can also judge different policies against benchmarks by examining their near-term carbon prices, which are shown for the different scenarios in Table 1, in 2005 dollars. A graphical comparison is shown in *SI Appendix*, Fig. S2. Carbon prices, equal to the Hotelling rents on carbon fuels in the baseline scenario, are essentially zero and are therefore not depicted. Prices under the optimal and temperature-limited scenarios at first rise to $38 and $79 per ton, respectively, by 2015. Prices under the optimal scenario then continue to rise sharply until they reach the projected backstop price.

Global average carbon prices under the two Copenhagen Accord scenarios are much lower than under the previous scenarios for the first 2 decades of the projections, reflecting the gradual introduction of policy interventions as well as incomplete participation. Note that the effective carbon price today (around $5 per ton) is well below that required under either the optimal or temperature-limited scenario. Numerical values for carbon prices for the different scenarios are reported in *SI Appendix*, Table S4, and those for the Copenhagen Accord with no trading are reported in *SI Appendix*, Table S5. *SI Appendix*, Tables S6 and S7 present the associated emissions control rates for the optimal case and the Copenhagen Accord with full trading.

Table 2 shows the large stakes involved in climate-change policies as measured by aggregate costs and benefits. Using the model discount rates, the optimal scenario raises the present value of world income by $8.1 trillion, or 0.35% of discounted income. This is equivalent to an annuity of $403 billion per year at a 5% annual discount rate. Imposing the 2 °C temperature constraint is quite costly, reducing the net benefit by almost half, because of the difficulty of attaining that target with so much inertia in the climate system. The Copenhagen Accord with phased-in participation of developing countries has substantial net benefits, but lack of participation in the "rich-only" case reduces these substantially. Fig. 4 shows the path of net costs as a percentage of income for seven major regions. Costs rise gradually over the coming decades and reach around 1% of national income for the high-income countries in the mid-21st century.

There are many conclusions that can be drawn from the present modeling effort. One important result is that even if countries meet their ambitious objectives under the Copenhagen Accord, global temperatures are unlikely to keep within the objective of 2 °C. This conclusion is reinforced if developing countries delay their full participation beyond the 2030–2050 time frame.

Comparisons with Other Studies. The results here can be compared with those of earlier versions of the RICE model as well as with those of other modeling groups. The details of the comparisons are available in *SI Appendix*. The temperature projections of the RICE-2010 model are substantially similar to those of the earliest vintages (*SI Appendix*, Fig. S3). The damage ratio (ratio of climate damage to output) is similar to that found in earlier versions for the first century, but the latest version projects higher damage ratios in the more distant future because of the inclusion of SLR (*SI Appendix*, Fig. S4). The optimal carbon price in the near term is substantially higher than in earlier versions (*SI Appendix*, Fig. S5). For example, that price for 2015 is ≈$40 per ton carbon, whereas in the early vintages, the optimal carbon price was in the $10–15 range. The major factors accounting for this difference are a major upward revision of global output with adoption of purchasing-power parity income measurement, higher temperature sensitivity, and lower discount rate on goods (25).

The results can also be compared with the latest round of model comparisons done for the Energy Modeling Forum 22 (EMF-22) (14). The closest comparison is the path of CO_2 concentrations for the 2000–2100 period for the RICE baseline and EMF-22 reference path. The RICE-model concentrations path is above the median of the 10 models with complete data. For the terminal year of 2100, the 10th, 50th, and 90th percentiles of CO_2 concentrations for the EMF-22 are 643, 754, and 910 ppm, whereas the RICE-model projection for 2100 is 793 ppm (a more detailed comparison is provided in *SI Appendix*, Fig. S6). The EMF-22 projections also indicate the difficulty of attaining the 2 °C objective (14).

Note that the optimal carbon prices in the RICE model are well below those in studies with very low discount rates, particularly those in the Stern Review (26, 27). Discussions about discounting involve unresolved issues of intergenerational fairness, aversion to inequality, and projections about future technological change and population growth as well as the appropriateness of the utilitarian framework used in the Ramsey model (5, 28, 29).

Another important area for analysis is the uncertainty associated with projections and policy analysis. Integrated assessment models are useful in making estimates of systemic uncertainty because they can incorporate all elements of the model and parameters. Estimating uncertainties and the benefits of better scientific knowledge is an important item on the research agenda (25).

Table 1. Carbon prices in the different runs

	2005 prices per ton of carbon						
Carbon prices	2005	2010	2015	2020	2025	2055	2105
Optimal	0.00	28.90	37.96	49.87	65.50	155.55	408.48
Limit temperature change <2 °C	0.00	58.92	79.04	106.03	142.25	521.78	903.69
Copenhagen: full trade	0.00	0.10	0.39	1.51	5.79	358.37	593.10
Copenhagen: rich only	0.00	0.07	0.39	2.21	12.40	64.11	27.68

The carbon prices are the market prices that are required to attain the policy objectives. These assume full trading and participation in all regions that are in the policy regime.

Table 2. Present value of consumption, different policies (scaled to 2005 US international dollars, 2005 prices)

Policy scenario	Present value utility Trillions of 2005 $	Difference		Annualized*
		Trillions of 2005 $	Percentage of base	Billions of $ per year
Base	2,301.5	0.00	0.00%	0
Optimal	2,309.6	8.06	0.35%	403
Limit temperature change <2 °C	2,305.9	4.37	0.19%	219
Copenhagen: full trade	2,307.8	6.26	0.27%	313
Copenhagen: no trade	2,307.1	5.63	0.24%	281
Copenhagen: rich only	2,304.1	2.55	0.11%	128

The estimates are the present value of consumption equivalent for the entire period. The difference in numerical column 2 shows the difference between the control run and the no-policy or baseline run. Incomes of countries are calculated using purchasing-power parity exchange rates and are discounted using an international interest rate that is the capital-weighted average of the real interest rates for different regions.

*Annual value of consumption at a discount rate of 5% per year.

Cautionary Notes

Analyses using integrated assessment economic models present an unrealistically smooth picture of the functioning of economic and political systems in much the same way that global climate models cannot capture the turbulence of weather systems. I conclude with four cautionary observations about the difficulties that arise in forging effective programs to slow climate change.

A first issue arises because of the strategic relationship between costs of abatement (which are thoroughly local) and avoidance of climate damage (which is a widely dispersed Samuelsonian public good). This structure of local costs and dispersed benefits leads to strong incentives to free riding: Each country has little incentive to take action and will benefit greatly if everybody else abates. This situation is analyzed using the Nash equilibrium concept from game theory. A Nash, or noncooperative, equilibrium results when no player can find a strategy to improve his or her payoff assuming that the other players stick to their strategies (30). A Nash equilibrium does not rule out any climate-change policies. Rather, noncooperative behavior implies that countries take abatement actions only to the extent that they themselves benefit and the benefits to the rest of the world are ignored.

Earlier studies have found that a Nash equilibrium would lead to carbon prices and emissions reductions that are much lower than optimal (17, 31, 32). Similar results are found in the RICE-2010 model. If we assume that each of the 12 regions acts noncooperatively, carbon prices are calculated to be approximately 1/10th of the optimal levels (*SI Appendix*, Table S8). (This may actually overstate noncooperative abatement because it assumes that countries within large regions such as Latin America coordinate their strategies.) The strategic significance of this finding is that countries will have strong incentives to free ride by not participating or to "cheat" on strong climate-change agreements. If they hide emissions or overstate reductions, their own economic welfare will improve even though others' welfare will deteriorate.

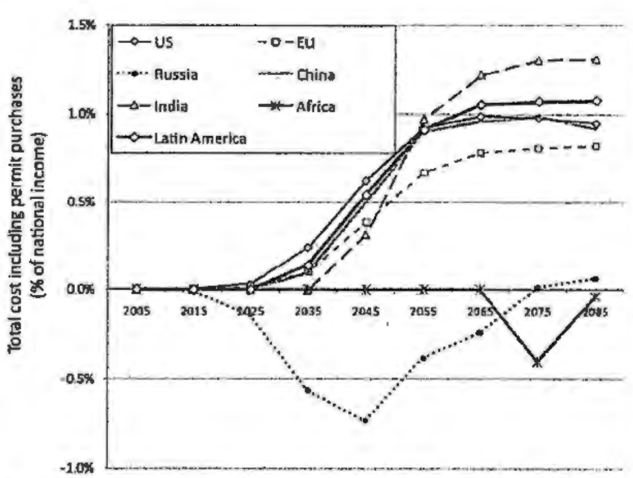

Fig. 4. Total costs of compliance as percent of national income. EU, European Union.

The difficulty of escaping from a low-level noncooperative equilibrium is amplified by a second factor, the intertemporal tradeoff. Climate-change policies require costly abatement in the near term to reduce damages in the distant future. The generational tradeoff is shown in Table 3. The last line shows the difference in global discounted damages and discounted abatement costs through 2055 between the outcome under the Copenhagen Accord and that in the baseline scenario. Abatement costs are more than five times the averted damages. For the period after 2055 (not shown), however, the ratio is reversed: Damages averted are more than four times abatement costs. Asking present generations—which are, in most projections, less well off than future generations—to shoulder large abatement costs would be asking for a level of political maturity that is rarely observed. The delayed payoffs reinforce the incentives of the noncooperative equilibrium, so the temptation is high to postpone taking the costly steps to reduce emissions.

A third issue arises because of the spatial asymmetry between winners and losers among countries. The trajectory of net costs for selected countries is shown in Fig. 4, and the numerical net costs in 2055 are shown in the last column of Table 3. The regions designated to undertake the largest emissions reductions under the Copenhagen Accord are the United States, China, and the European Union: The price tag for these regions totals more than $1 trillion in discounted costs through 2055. Several other regions, particularly Russia, can expect net benefits in a trading regime because they have been allocated excess emissions permits. Although poor countries can present reasoned arguments why rich countries should take the major emissions cuts, rich countries will weigh their own costs and attempt to share the burden more widely. This asymmetry reinforces the tendency of countries to move to their noncooperative equilibrium, resulting in an "aprés vous" syndrome in which no country takes substantial steps.

A final difficulty arises because the Kyoto and Copenhagen regimes have adopted a cap-and-trade structure. These have the theoretical advantage that they can coordinate emissions reductions across countries in an efficient manner. However, these theoretical advantages have proved illusory to date. Analysts who have examined the actual functioning of similar quantitative restrictions in different sectors note many difficulties with cap-and-trade that are not fully appreciated in the scientific community (33, 34). Economists often point to harmonized carbon taxes as a more efficient and attractive regime, but these have been generally

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Table 3. Costs and benefits of Copenhagen Accord through 2055

Region	Change in damages	Abatement costs	Permit purchases	Net costs
	Costs and benefits (billions of US dollars, discounted through 2055)			
United States	−51	328	228	505
European Union	−56	160	171	276
Japan	−12	44	64	96
Russia	−5	92	−176	−89
Eurasia	−4	62	−150	−92
China	−52	655	−268	335
India	−54	185	−1	130
Middle East	−47	123	−134	−57
Africa	−41	0	0	−41
Latin America	−33	127	154	248
OHI	−18	96	48	126
Other	−42	188	64	209
World	−413	2,060	0	1,647

The table illustrates the regional asymmetry of the Copenhagen Accord. The estimates take the present value of abatement costs and averted damages using the capital-weighted international real interest rate. The last column is the sum of the first three columns. OHI, other high income.

shunned in negotiations, particularly in the United States, because of the taboo on considering tax-based systems (35).

The results of the present study suggest that several policies could limit our "dangerous interference" with the climate system at modest costs. However, such policies would require a well-managed world and globally designed environmental policies, with most countries contributing, with decision makers looking both to sound geosciences and economic policies. Moreover, rich countries must bring along the poor, the unenthusiastic, and the laggard with sufficient carrots and sticks to ensure that all are on board and that free riding is limited. The checkered history of international agreements in areas as diverse as finance, whaling, international trade, and nuclear nonproliferation (36) indicates the extent of the obstacles on the road to reaching effective international agreements on climate change.

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ECONOMIC COMPETITION AMONG JURISDICTIONS: EFFICIENCY ENHANCING OR DISTORTION INDUCING?

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This paper explores the normative implications of competition among 'local' jurisdictions to attract new industry and income. Within a neoclassical framework, we examine how local officials set two policy variables, a tax (or subsidy) rate on mobile capital and a standard for local environmental quality, to induce more capital to enter the jurisdiction in order to raise wages. The analysis suggests that, for jurisdictions homogeneous in workers, local choices under simple-majority rule will be socially optimal; such jurisdictions select a zero tax rate on capital and set a standard for local environmental quality such that marginal willingness-to-pay equals the marginal social costs of a cleaner environment. However, in cases where jurisdictions are not homogeneous or where, for various reasons, they set a positive tax rate on capital, distortions arise not only in local fiscal decisions, but also in local environmental choices.

1. Introduction

The literature on local public finance contains two sharply contrasting themes. The first views interjurisdictional competition as a beneficent force that, similar to its role in the private sector, compels public agents to make efficient decisions. The cornerstone of this position is the famous Tiebout model (1956) in which individual households choose among jurisdictions in much the same way that they choose among sellers of private goods: an efficient provision of local public goods results from this process of 'voting with one's feet'. Likewise, in the more recent Leviathan literature that views government as a revenue-maximizing entity, competition among jurisdictions is seen as a powerful constraint on the undesirable expansionary tendencies of the public sector. Brennan and Buchanan (1980), for example, argue that

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competition among governments in the context of the 'interjurisdictional mobility of persons in pursuit of "fiscal gains" can offer partial or possibly complete substitutes for explicit fiscal constraints on the taxing power' (p. 184). Competition, by these arguments, can serve its welfare-enhancing 'disciplinary' function in the public, as well as the private, sector.

However, a second body of literature contends that interjurisdictional competition is a source of distortion in public choices. The general theme here is that in their pursuit of new industry and jobs, state and local officials will hold down taxes and other sources of costs to households and particularly to business enterprise to such an extent that public outputs will be provided at suboptimal levels. There are several strands to this line of argument. One focuses on 'tax competition' and contends that incentives to attract business investment will keep tax rates below levels needed to finance efficient levels of public services [Oates (1972, pp. 142–143)]. As Break (1967) has put it,

> The trouble is that state and local governments have been engaged for some time in an increasingly active competition among themselves for new business.... In such an environment government officials do not lightly propose increases in their own tax rates that go much beyond those prevailing in nearby states or in any area with similar natural attractions for industry.... Active tax competition, in short, tends to produce either a generally low level of state-local tax effort or a state-local tax structure with strong regressive features. (pp. 23–24).

Such 'cut-throat competition', as the ACIR (1981, p. 10) observes, has given rise to proposals for federal intervention to 'save the states from themselves'.

Cumberland (1979, 1981) has developed a second strand of the competition argument; it is his contention that local setting of standards for environmental quality would be subject to 'destructive interregional competition'. In their eagerness to attract new business and create jobs, state and local authorities, Cumberland argues, are likely to compete with one another by relaxing standards for environmental quality so as to reduce costs for prospective business firms. Cumberland concludes that national (minimum) standards for environmental quality are needed to prevent the excessive degradation of the environment that would result from state or local standard setting.

The distortion arguments are not, however, fully convincing. If existing residents care about public outputs (including environmental quality), and presumably they do, then tax or standard competition to attract economic activity imposes real costs on the citizenry. It is not at all clear that such competition is likely to extend to levels that ultimately result in suboptimal public outputs. Stigler (1957), for example, has contended that 'Competition of communities offers not obstacles but opportunities to various communities to choose the type and scale of government functions they wish' (p. 216). Nevertheless, the possibility of 'destructive competition' surely seems plausible and, in consequence, makes observers (like Cumberland) justifiably reticent to vest responsibility for setting environmental standards at state or local levels.

Part of the difficulty is that there exists little systematic analysis of these distortionary forms of interjurisdictional competition from which we can reach normative conclusions about local policy decisions.[1] The discussion is typically informal, often times anecdotal, and does not establish any soundly grounded results. Consequently, one may be geniunely disturbed by the possibly detrimental effects of tax and standard competition, but have little sense as to their likely importance.

It is our purpose in this paper to develop a simple model of interjurisdictional competition that can provide some insights into the basic normative issue. Using a standard kind of neoclassical model of production in tandem with a median-voter procedure for making local public decisions, we construct a model in which individual communities select both a tax rate on capital and a level of local environmental quality. We begin with a basic model of homogeneous 'worker' jurisdictions in which we find that simple-majority rule generates socially optimal decisions as regards both the taxation of capital and the setting of environmental standards. We then extend the model in two different ways. We introduce first a positive tax rate on capital that can have its source either in various realistic constraints on the choice of tax instruments or in a Niskanen-type of local government behavior; here we find outcomes involving not only fiscal distortions but also excessive degradation of the local environment. The second extension entails the introduction of mixed communities with both wage-earners and non-wage-earners. In this setting, the interests of the two groups within the community diverge, and the median-voter outcome is no longer socially optimal (unless some rather unlikely sorts of cooperation take place).

As this Introduction suggests, one of the interesting features of the model is that it incorporates into the decision process two distinct sources of interjurisdictional competition: local taxation and the choice of environmental standards. As the analysis will show, the joint determination of these two policy variables within a community can involve some intriguing interrelationships between revenue and environmental considerations.

2. The basic model

In this section we set forth a simple model that we believe captures the

[1]There is some recent theoretical work on tax competition. See, in particular, Mintz and Tulkens (1986), Wilson (1985, 1986), and Zodrow and Mieszkowski (1983, 1986).

spirit of interjurisdictional competition. In the model, jurisdictions compete for a mobile stock of capital by lowering taxes and relaxing environmental standards that would otherwise deflect capital elsewhere. In return for an increased capital stock, residents receive higher incomes in the form of higher wages. The community must, however, weigh the benefits of higher wages against the cost of forgone tax revenues and lower environmental quality.

We envision with a large number (say n) of local jurisdications, where the jurisdictions are sufficiently large that:

(i) individuals live and work in the same jurisdiction, and

(ii) pollution generated in one jurisdiction does not spill-over into another.

Suppose that each of these n jurisdictions produces a private good, Q, that is sold in a national market. Production requires capital, K, labor, L, and polluting waste emissions, E, where we treat E as a non-purchased input. We posit further than the production function exhibits constant returns to scale and possesses all of the nice curvature properties of a standard neo-classical production function.

An important part of the model is the specification of local environmental policy and the way in which it impinges on local productive activity. We shall assume that the local government sets a standard for local environmental quality: it specifies, for example, that the concentration of pollutants in the environment shall not exceed some physical quantity. This standard then translates into a limitation on the aggregate level of waste emissions in the locality. The local environmental authority thus effectively determines $\sum E$ for the jurisdiction. We will assume further that this aggregate is allocated among firms according to some measure of their level of productive activity. More precisely, we posit that a firm's allowable emissions are directly proportional to its labor force. Environmental policy thus determines the emissions–labor ratio, α, in the jurisdiction.[2] If we define k to be the capital–labor ratio, we can write the production function for a particular jurisdiction as:[3]

$$\begin{aligned} Q &= F(K, L, E) \\ &= Lf(k, \alpha). \end{aligned} \tag{1}$$

[2]There are obviously other ways in which one could specify the form of local environmental policy. The form we have chosen, in addition to seeming reasonable, facilitates the analysis. As will become evident, it allows us to capture the effects of environmental policy both on environmental quality and on the production of output in terms of a single parameter, α, that enters both the production and utility functions. It is not inconsistent, incidentally, for α to correspond both to a particular level of aggregate emissions and to a specific emissions–labor ratio, for (as we will note shortly) the labor input in a jurisdiction is taken to be fixed. Finally, we stress that none of the basic results of the paper changes if communities use certain other policy tools such as Pigouvian taxes on emissions rather than the command and control strategy we have assumed here. See Oates and Schwab (1987) for a discussion of this point.

[3]For notational simplicity, we shall not employ a superscript to denote a particular jurisdiction, although the functions are understood to be jurisdiction-specific.

While the production function exhibits constant returns to scale in all inputs, the nature of environmental policy allows firms to act as though there were constant returns to scale in just the purchased inputs, capital and labor. If a firm doubles its input of labor, it is allowed to double emissions; therefore, a doubling of capital and labor implies a doubling of all inputs and, hence, output. In equilibrium, we will then observe firms that are of finite (though indeterminate) size earning zero profits.

Throughout the paper we use subscripts to denote partial derivatives, and we therefore write the marginal products of capital, emissions, and labor as f_k, f_α, and $(f-kf_k-\alpha f_\alpha)$. We assume that marginal products are diminishing and that increases in α raise the marginal product of capital; f_{kk} and $f_{\alpha\alpha}$ are therefore negative and $f_{k\alpha}$ is positive.

We also assume that there is a fixed stock of capital in this society which is perfectly mobile (at least in the long run) across jurisdictions. This capital is distributed so as to maximize its earnings, which implies that the return to capital, net of any local taxes, will be equated across jurisdictions.[4] All of the communities are small in the sense that they treat this rate of return as a parameter. This is analogous to an assumption of perfect competition in product markets; just as perfectly competitive firms believe they have no influence on price and therefore behave as price-takers, these competitive communities take the rate of return on capital as given.[5] The community raises tax revenues by levying a tax of t dollars on each unit of capital; per capita tax revenue T is then tk.[6] Capital receives its marginal product f_k, and therefore given some rate of return r available in other jurisdictions, the local stock of capital will adjust so that

$$f_k - t = r. \tag{2}$$

Labor, in contrast, is perfectly immobile.[7] We assume initially that each

[4]We assume that the ownership of capital in this society has been determined exogenously. There is no requirement in the model that people necessarily own capital in their community; capital is traded in a national market.

[5]For a model more in the spirit of 'imperfect competition' in which there is explicit interaction between the policy decisions of two competing jurisdictions, see Mintz and Tulkens (1986).

[6]We can extend the model by introducing local public goods that provide services to capital such as roads and police and fire protection. Suppose that each unit of capital requires services which cost s dollars. If the tax rate on capital is t', then we can think of t as the difference between t' and s (i.e. as the tax on capital in excess of the cost of services consumed by capital). t, incidentally, can be negative in which case it would indicate a unit subsidy to capital.

[7]We assume labor to be immobile for two reasons. First (and most obvious), it greatly simplifies the analysis. And, second, it seems an appropriate assumption in view of the policy problem under study. More specifically, we are considering the decisions of a given population as they relate to the inflow and outflow of business investments that generate 'local' income. The analysis thus focuses on how existing residents view the effect of their collective choices on interjurisdictional movements of capital. However, as we have shown in Oates and Schwab (1987), all of the basic results in this paper emerge from a model in which labor is perfectly mobile and the size of each community is fixed. We thank Robert Lee for raising the mobility issue with us.

community consists of individuals identical in both tastes and productive capacity and whose pattern of residence across jurisdictions is 'historically determined'. Each individual puts in a fixed period of work (e.g. a 40-hour week). The labor market is perfectly competitive, and the real wage w equals the gains from hiring an additional worker. w is then the sum of (i) the marginal product of labor, and (ii) the additional output stemming from the increase in permitted emissions, αf_α; under constant returns to scale, w then equals $(f-kf_k)$.

Each of the identical residents receives utility from consumption c and from the local level of environmental quality. Since environmental quality depends on the local choice of α, we can write

$$u=u(c,\alpha), \tag{3}$$

where u is a quasi-concave function that is increasing in c, but decreasing in α (i.e. α is a 'bad', and therefore u_α is negative).

Each resident's income consists of an exogenous component y, wages w, and tax revenues T collected from capital.[8] The budget constraint for any representative individual then requires:

$$\begin{aligned} c &= y+w+T \\ &= y+(f-kf_k)+tk. \end{aligned} \tag{4}$$

Note that an individual has two roles here. First, he is a consumer, seeking in the usual way to maximize utility over a bundle of goods and services that includes a local public good, environmental quality.[9] And, second, he supplies labor for productive purposes in return for his income. From the latter perspective, residents have a clear incentive to encourage the entry of more capital as a means to increasing their wages. But this jurisdiction must compete against other jurisdictions. To attract capital, the community must reduce taxes on capital (which lowers income and, therefore, indirectly lowers utility) and/or relax environmental standards (which lowers utility directly). These are the tradeoffs inherent in interjurisdictional competition.

[8] It is easiest to think of the tax revenues from capital simply being distributed on an equal per-capita basis to the residents of the community; this is how we shall treat these revenues. Alternatively (and equivalently), we could envision these revenues as being employed to finance outputs of various local public goods with a corresponding reduction in local tax payments by residents.

[9] For simplicity, we have not, at this juncture, incorporated into the model the rest of the public sector. Instead, we simply assume that, behind the scenes, the local government provides efficient quantities of the various local public goods which it finances through the imposition of lump-sum taxes. We return to this matter later.

2.1. The median-voter outcome

The interesting normative issue here is whether there is any systematic tendency for residents to choose other than optimal values for α and t. To address this issue, we must specify a collective-choice rule for the determination of these two policy parameters and then compare the outcome under this rule to the socially optimal outcome. For this purpose, we adopt in this section the widely used median-voter model as the mechanism for determining α and t. Since all individuals within a jurisdiction are in every respect identical, we can determine the median-voter outcome by maximizing the utility of any representative consumer.[10] Formally, the median-voter model requires the maximization of the utility function in eq. (3) subject to the budget constraint in (4) and the constraint on the rate of return in (2).

The first-order conditions for the solution to this problem are:

$$u_c = \lambda_1, \tag{5a}$$

$$u_\alpha = \lambda_1 f_\alpha - (\lambda_2 - \lambda_1 k) f_{k\alpha}, \tag{5b}$$

$$\lambda_1 t = (\lambda_1 k - \lambda_2) f_{kk}, \tag{5c}$$

$$\lambda_2 = \lambda_1 k, \tag{5d}$$

where λ_1 is the Lagrange multiplier associated with the budget constraint and λ_2 is the Lagrange multiplier associated with the constraint on the rate of return. From these conditions, we find that maximization requires:

$$t = 0, \tag{6a}$$

$$-u_\alpha / u_c = f_\alpha. \tag{6b}$$

Eq. (6a) indicates that the community should set the tax rate on capital exactly equal to zero. It should neither try to attract capital by offering a subsidy ($t<0$), nor try to raise any revenue by taxing capital ($t>0$).[11] Eq. (6b) says that the community should choose a combination of consumption and environmental standards such that its marginal rate of substitution between the two is equal to f_α, the 'marginal product of the environment'.

[10] With identical persons, we could just as well invoke a beneficent local official who chooses the parameters of public policy so as to maximize the welfare of the residents of the jurisdiction.

[11] If capital requires local public services (see footnote 6), then (6a) would indicate that the community should set a tax on capital which exactly covers the cost of those services. Where head taxes are available, Zodrow and Mieszkowski (1983) also find that a tax rate of zero on capital is optimal.

We offer the following interpretation of these results. The rate of return constraint implies that we can write the community's budget constraint:

$$c = y + (f - kf_k) + (f_k - r)k$$
$$= y + (f - rk). \tag{4'}$$

Wage and tax income are thus always equal to the surplus which remains after output has been sold and capital receives its market-determined rate of return. The community is much like a perfectly competitive firm that has a fixed quantity of labor but can vary its capital. Like such a firm, the community maximizes its net income by choosing a capital stock such that the marginal product of capital, f_k, equals its price, r. But if f_k equals r, then the tax rate, t, must be zero; the community thus takes all its surplus in the form of wages and none as tax revenues.

We can gain further insight into the setting of environmental policy as described in eq. (6b) by considering the impact of a small change in α on consumption. From the budget constraint, the change in consumption is the sum of the change in the wage and the change in tax revenues. We thus see that environmental policy has two distinct effects on consumption: a 'wage effect' and a 'fiscal effect'.

Consider first the wage effect. Differentiation of the wage equation shows that a tightening of environmental policy taking the form of a decrease in α of $\mathrm{d}\alpha$ would reduce wages by $(f_\alpha - kf_{k\alpha})\,\mathrm{d}\alpha$ if the capital stock remained constant. This is the direct effect. Tightening environmental policy, however, must cause the capital stock to fall in order to maintain the rate of return r, and therefore the wage rate falls further. If the change in the capital stock is $\mathrm{d}k$, then this additional change in w must be $-(kf_{kk})\,\mathrm{d}k$; total differentiation of eq. (2) shows that $\mathrm{d}k$ must equal $-(f_{k\alpha}/f_{kk})\,\mathrm{d}\alpha$, and therefore the indirect effect of tightening environmental standards is a fall in the wage of $kf_{k\alpha}\,\mathrm{d}\alpha$. The sum of the indirect and direct effects of a decrease in α on the wage is thus $f_\alpha\,\mathrm{d}\alpha$. This is the wage effect of environmental policy.

Now consider the fiscal effect. The change in tax revenue, $\mathrm{d}T$, is $t\,\mathrm{d}k$. From the discussion above, $\mathrm{d}k$ is $-(f_{k\alpha}/f_{kk})\,\mathrm{d}\alpha$, and therefore the fiscal effect of environmental policy must be $-t(f_{k\alpha}/f_{kk})\,\mathrm{d}\alpha$.

The total effect of a decrease in α on consumption is then:

$$\mathrm{d}c = \mathrm{d}w + \mathrm{d}T$$
$$= f_\alpha\,\mathrm{d}\alpha - t(f_{k\alpha}/f_{kk})\,\mathrm{d}\alpha. \tag{7}$$

However, if the tax rate has been set equal to zero, the fiscal effect vanishes; the change in consumption, in this case, is simply equal to the change in the wage, $f_{\alpha}\,d\alpha$. Maximizing behavior thus implies that the community will set α so that the change in wage income equals the marginal willingness-to-pay for environmental quality, $-u_{\alpha}/u_c$. But the change in wage income, as we see from (7) with $t=0$, is precisely equal to the increment in output associated with a marginal change in environmental policy. Since the wage effect equals the 'output effect' of a marginal change in α, we find in (6b) that local environmental decisions are such that the marginal willingness-to-pay for environmental quality equals the 'marginal product' of the environment.

It is important to stress that the determination of the environmental standard and the tax rate on capital are closely intertwined. In particular, if the tax rate (for whatever reason) is non-zero, then the marginal rate of substitution will no longer equal the marginal product of the environment, since in that case the fiscal effect will not vanish. We return to this issue in section 3 of the paper.

2.2. *Efficiency in the basic model*

We know that perfect competition among firms leads to efficiency; we wish to know if competition among communities also fosters efficiency. Efficiency requires that we maximize the utility of a representative consumer in one community subject to three constraints: (i) we allow a representative consumer in every other community to reach a specified level of utility (which may vary across communities), (ii) aggregate production in the society equals aggregate consumption, and (iii) we allocate society's stock of capital among the n communities. The necessary conditions for the solution to this problem require:

$$-u_{\alpha}^{i}/u_{c}^{i}=f_{\alpha}^{i}, \quad i=1,2,\ldots,n, \tag{8a}$$

$$f_{k}^{i}=f_{k}^{j}, \quad i,j=1,2,\ldots,n. \tag{8b}$$

where the superscripts refer to communities.

As we argued above, if eq. (8a) did not hold in some community, then it would be possible to change α and consumption in that community so as to increase welfare; if (8b) did not hold, it would be possible to increase aggregate output by moving capital from a community where the marginal product of capital is low to a community where it is high.[12]

It is clear that these conditions will be satisfied under the basic model we have described. The aggregate demand for capital at some rate of return r is the horizontal summation of the communities' demand curves. The market will clear at a rate of return r^* which equates aggregate demand and

[12] Note that since environmental quality is a non-traded good, it is not necessary that the marginal product of the environment or the marginal rate of substitution between consumption and the environment be equal across communities.

society's fixed stock of capital. We showed that all communities would set a tax rate of zero, and therefore the marginal product of capital in all communities will be r^*, satisfying (8b). We also showed that if each community maximizes the utility of a representative consumer, then it will equate the marginal rate of substitution between c and α and the slope of the consumption possibility curve, thereby satisfying (8a). In our basic model, competition among jurisdictions is thus conducive to efficient outcomes.

We can offer the following interpretation of these results. We showed above that the marginal private cost of improving environmental quality (measured in terms of forgone consumption) must be f_α, inasmuch as f_α is the change in the wage and there is no fiscal effect of environmental policy when the tax rate is set at its optimal level of zero. We also showed that the community maximizes utility by equating the marginal private cost of improving environmental quality and marginal private benefit. But clearly, f_α is also the marginal social cost of tightening standards, since f_α represents society's forgone consumption. Thus, utility-maximizing behavior promotes efficiency in this model because society's and the community's evaluation of the costs and benefits of environmental policy are identical.[13]

3. The interaction between tax and environmental policies

We showed above that if communities set the optimal tax on capital of zero, then competition would lead jurisdictions to establish efficient standards for environmental quality. As we discuss below, however, communities may choose to tax or subsidize capital for a variety of reasons. In this section of the paper we examine the choice of environmental policy when tax policy has not been set optimally.

3.1. Capital taxation as a 'second-best' tax

Communities may be forced to tax capital if they are unable to finance local public goods by imposing a non-distorting tax such as a head tax; fiscal constraints may thus result in the adoption of a levy on capital as a 'second-best' tax. Recently, Wilson (1986), Zodrow and Mieszkowski (1986), and Wildasin (1986) have shown that communities will underprovide local public goods if they must rely on a tax on capital. The argument is basically as follows. Communities realize that as they raise the tax rate to finance the

[13]Given our assumption that jurisdictions are sufficiently large that pollution created in one jurisdiction does not spill-over into another, there is no divergence between the marginal private benefit and marginal social benefit of reducing pollution. If there exist any interjurisdictional externalities occasioned by the transport of pollution from one community to another, then (for the usual sorts of reasons) local choice will not generate a socially optimal outcome. For an excellent general treatment of a variety of interjurisdictional externalities, see Gordon (1983).

local public good, they will drive out capital. Thus, they raise the tax rate only to the point at which the cost of the public good, including the negative effects of a smaller capital stock, equals the benefits. But as Wildasin (1986) explains, the social cost of local public goods is less than the private cost, since capital that leaves one community will be deflected to another. Thus, underprovision of local public goods arises, because communities fail to take into account the beneficial externalities they confer on other communities.

Our purpose in this section is to show that the taxation of capital also distorts the choice of environmental standards. One way to establish this point is to introduce a local public good explicitly into the median-voter model developed in section 2 of the paper; in the presence of such a good, tax revenues must be positive. We present such an expanded model in the appendix. But we can also make our basic point somewhat more simply.

Suppose the community has chosen some positive tax rate t. We might then ask what level of environmental policy α the community should choose in order to maximize $u(c,\alpha)$ subject to the rate of return constraint in (2) and the budget constraint in (4). The analog to eq. (6b) for this problem is

$$-u_\alpha/u_c = f_\alpha - t(f_{k\alpha}/f_{kk}). \tag{9}$$

It is clear in (9) that the social benefit from improving the environment, $-u_\alpha/u_c$, will exceed social cost, f_α, inasmuch as all of the terms on the right-hand side are positive except f_{kk}; therefore, environmental quality is set at an inefficiently low level. This contrasts with our earlier result where we found that social costs and benefits would be equal if the community chose the optimal tax rate of zero.

The interpretation is straightforward. From the discussion of eq. (7), it is clear that the first term on the right-hand side of (9) is the wage effect of environmental policy and that the second term is the fiscal effect. Thus, (9) shows that the community will continue to tighten environmental standards to the point that willingness to sacrifice the composite good equals the *sum* of lost wages and forgone tax revenues. The lost wages, as shown above, are equal to lost output (i.e. the wage effect equals the output effect); the forgone tax revenues (the fiscal effect) thus represent a wedge between the private and social cost of improving the environment.

3.2. *An alternative model of public choice*

We can get a result similar to that in the preceding section without actually constraining the community to tax capital. Instead, we can invoke the spirit of some of the recent public-choice literature which posits that government agencies have their own set of concerns in the political arena that typically are not in complete harmony with the interests of their constituents. One common hypothesis [with Niskanen (1977) as its source] is that bureaucrats seek to maximize their budgets. Salary, perquisites of office, reputation, power, and the capacity to award patronage typically rise as the agency's budget expands.

In the Niskanen spirit, we thus specify a government objective function, g, which has two arguments: revenues from the taxation of capital T (which are equal to tk) and the utility of a representative voter:

$$g=g[T, u(c,\alpha)], \tag{10}$$

where we would expect the partial derivatives of g with respect to T and u to be positive. We include the utility of voters since government, even if its central concern is to maximize its own welfare, cannot entirely ignore the well-being of its constituents. We thus envision a government which must balance its desire to realize the benefits of higher taxes today against the possibility that the voters will 'turn the rascals out' tomorrow.

It is not difficult to show that the maximization of this objective function subject to the community's budget constraint and the constraint on the rate of return on capital implies that government will set a positive tax rate on capital and that the marginal social benefit of further improving the environment will exceed marginal social cost, i.e. environmental quality will be set at an inefficiently low level. The intuition behind these results is straightforward. The Niskanen public agent derives utility from increased tax revenues. This provides an incentive to entice capital into the jurisdiction with lax environmental standards so as to increase the tax base. Thus environmental policy again has a fiscal effect as it provides a further means by which the bureaucrat can generate additional tax revenue, and this fiscal effect leads to excessive local pollution.

3.3. *Efficiency under distorting taxes on capital*

Our analysis of the interaction between tax and environmental policies suggests that it is important to pay close attention to the notion of efficiency. We argued above that if an omnipotent planner faced only the three constraints we described, then, as shown in (8a), this planner would choose an environmental standard for each community such that $-u^i_\alpha/u^i_c$ equals f^i_α. It is not true, however, that (8a) is the efficiency condition for the choice of an environmental standard in the presence of distorting local taxes on capital.[14]

To see this point, consider the special case where the society consists of

[14] We thank an anonymous referee for bringing this issue to our attention and working out its implications.

only two communities. Suppose we wish to maximize the utility of community 1 residents subject to the constraints that we allow community 2 residents to reach some given level of utility, that consumption equal production, and that we allocate society's fixed stock of capital between the two communities; a fourth constraint requires that there be a wedge between the marginal product of capital in the two communities of (t^1-t^2). The solution to this probem requires:

$$-u_a^1/u_c^1 = f_a^1 - (t^1-t^2)[f_{ka}^1/(f_{kk}^1+\mu f_{kk}^2)], \tag{11}$$

where μ is the ratio of the number of workers in the two communities, L^1/L^2.

Clearly, if (t^1-t^2) were zero, then (11) reduces to (8a). If this wedge is positive, however, then efficiency requires the marginal social benefit from reducing pollution in community 1, $-u_a^1/u_c^1$, to exceed the marginal product of the environment in 1, f_a^1. The explanation is as follows. If the environmental standard in 1 were relxed, capital would flow from 2 to 1 in order to maintain the wedge between the marginal product of capital in the two communities. Aggregate output would rise by the product of the difference in marginal products and the flow of capital. Efficiency requires us to loosen the standard in 1 to the point that the marginal social loss from increased pollution equals the gain in output. Thus, communities that set high tax rates should set relatively lax environmental standards to offset the distortions introduced by fiscal policy.

4. Another extension of the basic model: Environmentalists vs. advocates of economic growth

While we believe that our simple model captures the spirit of interjurisdictional competition, there is an important intrajurisdictional dimension to such behavior that cannot be addressed in a model with a homogeneous population. In particular, several empirical studies stress that the 'environmental–jobs' tradeoff often involves an intense conflict of interest among different constituencies within the local community. There are frequently conservationist groups whose opposition to economic development and the associated environmental degradation runs directly counter to the interests of those whose employment and income depend on the entry of new industry. Deacon and Shapiro (1975), for example, in a study of voting behavior on a conservationist measure in California, found a significant propensity for 'laborers and construction craftsmen' to oppose the conservation act, reflecting presumably their preference for economic development and new jobs. Likewise, in a study of a pulp-mill referendum in New Hampshire, Fischel (1979) found systematic tendencies for 'laborers' to favor the mill and for 'professionals' to oppose it. This suggests that we extend the model to encompass individuals with different circumstances and interests, and observe how this affects local decisions on public outputs and taxes.

To put the results in the sharpest perspective, we return to our basic model and introduce one new element. We assume that the community now contains two types of people. The first type are, like before, wage-earners; for them, the presence of more capital implies a higher wage rate, and, hence, an increase in income. In contrast, the other subset consists of individuals who have no wage income. Members of this second group have an exogenous component of income supplemented by their share of revenues from the taxation of capital. There thus arises a potential conflict of interest between the two groups in the community: workers, L, have an incentive to encourage the influx of capital as a source of higher wage income, while non-wage-earners, N, without this incentive are likely to be more concerned with the environmental deterioration that can accompany an increased stock of capital. The two groups are unlikely to see eye-to-eye on the tradeoff between environmental quality and jobs. We shall characterize outcomes in such a divided community for two distinct cases: a worker majority and a non-worker majority.

4.1. Worker-majority outcome

Let us assume first that the group of workers constitutes the majority (i.e. $L>N$) and that, under median-voter rule, this group enforces its will on the community as a whole. Assuming (as before) that workers are homogeneous in every way, we need simply maximize the utility of a representative worker subject to the relevant constraints. On first inspection, this would seem to pose an identical problem to that in our initial model. However, this is not quite so; there is an important difference with significant implications for the outcome. In particular, the presence of non-wage-earners introduces an asymmetry affecting wage income, but not the division of tax revenues. Instead of eq. (4), the budget constraint for the representive worker becomes:

$$c = y^l + w + T$$

$$= y^l + f - kf_k + \theta tk, \tag{4''}$$

where $\theta = L/(N+L)$ and y^l is per-capita exogenous income for wage-earners. In the last term on the RHS of (4″), we now have the parameter θ, reflecting the (equal) division of tax revenues among non-wage-earners as well as workers. The presence of θ results in certain changes in the first-order conditions; in place of (5a) through (5d), we now find that

$$u_c^l = \lambda_1, \tag{5a'}$$

$$u_\alpha^l = -\lambda_1 f_\alpha - (\lambda_2 - \lambda_1 k) f_{k\alpha}, \tag{5b'}$$

$$\lambda_1 t = \frac{1}{\theta}(\lambda_1 k - \lambda_2) f_{kk}, \tag{5c'}$$

$$\lambda_2 = \lambda_1 \theta k, \tag{5d'}$$

with the parameter θ entering into (5c') and (5d').

By suitable rearrangement, we find that utility maximization of the subset of workers requires [instead of (6a) and (6b) as earlier] that

$$t = \left(\frac{1-\theta}{\theta}\right) k f_{kk}, \tag{6a'}$$

$$\frac{-u_\alpha^l}{u_c^l} = f_\alpha - \theta t \frac{f_{k\alpha}}{f_{kk}}. \tag{6b'}$$

In contrast to our earlier results, workers no longer desire a zero tax rate on capital; in fact, (6a') is unambiguously negative, indicating that the worker-determined outcome implies a subsidy to capital. The rationale for this result is clear. Workers reap all the gains from the increased wage income associated with a larger capital stock, but they no not bear the full cost of the subsidy to capital – some of the cost of the subsidy falls on non-wage-earners. Thus, a small change, dt, from zero in a negative direction yields an increase in wages (that although equal to the subsidy to capital) exceeds the part of the subsidy subscribed by the group of workers.

Similarly, we find a change in moving from (6b) to (6b'); workers, in a sense, now prefer a somewhat higher level of environmental quality as their marginal rate of substitution is now less than f_α. This result reflects the fiscal effect of environmental policy; since t is negative, workers must take into account their share of higher subsidy payments if they choose to increase α. Workers therefore find it in their interest to raise wages by subsidizing capital directly rather than by relaxing environmental standards.

4.2. Non-wage-earners in the majority

Our second case involving a majority of non-wage-earners (i.e. $N > L$) is more straightforward, since the tradeoff for these individuals is simply between environmental quality and revenues from the taxation of capital. Here we maximize the utility of a representative non-wage-earner subject to the relevant constraints – that is, we maximize (3) subject to (2) and the applicable budget constraint:

$$c = y^n + \theta t k, \qquad (4''')$$

where y^n is an exogenously-determined component of income. By suitable manipulation of the first-order conditions, we obtain:

$$t = -k f_{kk}, \qquad (6a'')$$

$$\frac{-u_\alpha^n}{u_c^n} = \frac{-\theta t f_{k\alpha}}{f_{kk}}. \qquad (6b'')$$

In contrast to (6a') for the workers, (6a'') is unambiguously positive: non-wage-earners desire a positive tax on capital. Eq. (6b'') embodies a pure 'fiscal effect' in the choice of environmental standards; it indicates that the MRS of non-wage-earners for environmental quality should be set equal to the marginal fiscal gains per capita from the taxation of capital. These two conditions, incidentally, imply a kind of Laffer-curve effect: if we hold α constant, we see that the derived tax rate on capital is such that the change in revenues from the tax is zero. To see this, let $T = \theta k t =$ per-capita revenues from the taxation of capital. Then,

$$\mathrm{d}T = \theta(k\,\mathrm{d}t + t\,\mathrm{d}k). \qquad (12)$$

From our return-on-capital constraint, $(f_k - t) = r$, we obtain $f_{kk}\,\mathrm{d}k = \mathrm{d}t$. Substituting this and (6a'') into eq. (12), we find that:

$$\mathrm{d}T = \theta(k f_{kk}\,\mathrm{d}k - k f_{kk}\,\mathrm{d}k) = 0. \qquad (13)$$

The results for our two special cases of worker-majority rule and a non-wage-earner majority make two basic points. First, the desired policies of the two groups clearly differ. Workers wish to subsidize capital in order to augment their wage income, while non-wage-earners, in contrast, want to tax capital as a source of revenues. Likewise, the two groups will prefer different levels of local environmental quality; there is some presumption that wage-earners will opt for a lower level of environmental quality (i.e. a higher value of α) than will non-wage-earners, although we have not been able to demonstrate this as a general result.[15]

[15] Eqs. (6a') and (6b') together imply that the wage-earner's marginal rate of substitution of consumption for environmental quality will be $(f_\alpha - k f_{k\alpha}) + \theta k f_{k\alpha}$; similarly, (6a'') and (6b'') imply that non-wage-earner's MRS will be $\theta k f_{k\alpha}$. $(f_\alpha - k f_{k\alpha})$ is the derivative of the wage rate with respect to α and is presumably positive. It does not seem possible, however, to determine whether the term common to both will take on a larger value in the wage-earner or non-wage-earner equation; we can establish that θ (by definition) is larger in the wage-earner case, but there seems to be no such general claim concerning the relative value of k and $f_{k\alpha}$. The terms that we can sign thus point to a higher MRS for wage-earners and suggest that wage-earners will choose a lower level of environmental quality. But this result is clearly not general; this would require a number of further assumptions regarding the preference functions and levels of relative income.

Second, it is evident that the outcome under a majority of either group is not socially optimal. The conditions for the maximization of social welfare are, as we saw earlier, satisfied by the median-voter outcome for a system of homogeneous jurisdictions of wage-earners. But if the jurisdictions are divided between workers and non-wage-earners, not only will there be a divergence of desired policies within each community, but the median-voter outcome will not, in either case, be an economically efficient one.[16]

In concluding this section, we would note that although we have framed the conflict of interests as involving environmentalists versus growth advocates, we have not assumed that there are any systematic differences in preferences between the two groups. One might, for example, postulate that certain groups possess utility functions that place a greater weight on environmental amenities than do those of others. However, it is not necessary to make such a distinction to provide a source for such conflicts of interest. In this section, the divergence of interests has its source solely in differing economic circumstances: the income of one group depends on the local stock of capital, while that of the other does not. The tension between the two groups thus represents a special case of a more general phenomenon under which one group attempts to use the fiscal system in order to 'exploit' the other. Workers attempt to saddle non-wage-earners with subsidies to capital that raises wages, while the latter group seeks to tax capital so as to enhance local revenues at the expense of wages. This model may, incidentally, have some explanatory power. As we have seen, the subsidization of capital makes little sense in our basic model with a homogeneous population. Yet we know that states and localities often engage in vigorous efforts to attract new business capital. Perhaps this is best understood as an effort of certain interest groups to further their ends at the expense of the remainder of the populace.

5. Summary and concluding remarks

To summarize our results, we present in table 1 the outcomes for our basic model of homogeneous jurisdictions of workers $[\theta = L/(L+N) = 1]$, for our

[16]The inefficiencies that characterize either outcome indicate that there are potential 'gains-from-trade' between the two groups in the setting of policy, since both of our majority-rule outcomes lie inside the utility-possibilities frontier. If there were some mechanism to reach a 'cooperative' solution, welfare gains would be possible. It is a straightforward matter to describe such a cooperative outcome by solving for the Pareto-efficiency conditions for the community as a whole. Such an exercise demonstrates that the cooperative solution involves zero taxation of capital and a Samuelsonian condition for the level of environmental quality. These conditions (like those for our basic model) satisfy the social optimality conditions for the system as a whole. It is not easy, however, to envision a mechanism to facilitate such cooperative action. There may in some instances exist other issues so that some kind of log-rolling maneuver may permit an approximation to the cooperative outcome. But, more generally, there do not seem to exist institutions to accommodate the necessary bargains.

Table 1

Summary of results.

Case	Tax rate	Marginal rate of substitution
$\theta=1$	$t=0$	$-\frac{u_x}{u_c}=f_x$
Tax-constrained	$t>0$	$-\frac{u_x}{u_c}=f_x-t\frac{f_{kx}}{f_{kk}}$
Niskanen	$t>0$	$-\frac{u_x}{u_c}=f_x+kf_{kx}\frac{g_T}{g_u u_c}$
$1/2<\theta<1$	$t=\left(\frac{1-\theta}{\theta}\right)kf_{kk}<0$	$-\frac{u_x^J}{u_c^J}=f_x-t\theta\frac{f_{kx}}{f_{kk}}$
$0<\theta<1/2$	$t=-kf_{kk}>0$	$-\frac{u_x^R}{u_c^R}=-t\theta\frac{f_{kx}}{f_{kk}}$

tax-constrained case, for our Niskanen model with revenue maximization, and for our two cases involving mixed jurisdictions. The homogeneous case generates a socially optimal outcome, while the remaining cases do not.

The results of the analysis are admittedly somewhat mixed, but they do have some interesting implications. For instances of relatively homogeneous communities where the benefits and costs of public programs are clearly understood and where public decisions reflect the well-being of the jurisdiction's residents, the analysis indicates that outcomes will tend to be roughly efficient. Such communities will tend to select both incentives for new industry and standards for local environmental quality that are socially optimal. In this regard Fischel (1975) demonstrated some years ago that, in a simple framework in which firms pay communities an entrance fee in compensation for environmental damage, a socially efficient allocation of firms and environmental quality results. Our basic model in a sense replicates Fischel's results, although the mechanism for compensation in our model – a higher wage – is somewhat different from the direct payment in the Fischel model. Nevertheless, it achieves the same result. In our basic model, interjurisdictional competition is efficiency-enhancing.

As we have seen, however, there are three distinct sources of potential distortion in local decision-making. First, if the jurisdiction does not have access to efficient tax instruments – if, as in our analysis, it is constrained to tax capital – then distortions occur in both fiscal and environmental decisions. More specifically, communities, because of the fiscal effects associated with environmental decisions, will opt for a socially excessive level of pollution. Second, if public decisions deviate from the will of the electorate (as in our Niskanen model), then efficient outcomes, not surprisingly, are not to be expected. In particular, we found that (as in the tax-constrained case) revenue-maximizing behavior will lead to excessive taxation of capital and suboptimal environmental quality in the jurisdiction. And third, conflicts of interest within a heterogeneous community can also introduce distortions into public decisions. Depending on which group gets the upper hand, such conflict can result in either the taxation or the subsidization of capital with consequent inefficiencies in decisions on environmental amenities.

In concluding the paper, there are two further issues that we wish to raise. The first concerns the meaning of the term 'local' in the analysis. We have used this term in a rather imprecise way to refer to units for decentralized decision-making. But the question arises as to the sorts of units to which the analysis would presumably be applicable. We can offer a few observations on this. It is clear that the units cannot typically be the smallest units of local government such as municipalities within a metropolitan area. As we noted earlier, the jurisdictions in our model are sufficiently large that residents live and work within their boundaries and that pollution generated in the area does not spill across these boundaries. This would suggest that the units suitable for decentralized choice under this framework would have to be at least as large as metropolitan areas and perhaps, in some instances, larger – state boundaries might, for certain pollutants and commuting patterns, provide the best approximation. At any rate our analysis clearly does not refer to the standard Tiebout kind of community where individuals may work in a jurisdiction other than that in which they reside. What is involved here are larger jurisdictions: metropolitan areas or perhaps even states or regions.

Second, our colleague Peter Murrell has raised a troublesome issue that we have not attempted to incorporate into the formal analysis: the well-being of future generations. Certain dimensions of environmental quality, if degraded by current generations, are not easily restored later. The development of wilderness areas and the creation of certain forms of long-lived, hazardous wastes come quickly to mind. The issue here is that the concern for future generations is, in one important sense, more difficult to incorporate in local policy decisions than at the national level. In particular, the well-being of one's own progeny is unlikely to depend in important ways on environmental decisions within one's present locality. An individual's children and their offspring will probably live elsewhere so that their 'environmental heritage' under a system of local decision-making will be determined by others. This may well result in a form of myopia under local standard-setting that leads to socially suboptimal levels of environmental quality for one's descendants. In principal, at least, more centralized decision-making should serve to 'internalize' these concerns and provide better representation of the interests of those yet to come. This is, however, a complicated matter. As William Fischel and Bruce Hamilton have pointed out to us, in a setting of mobile individuals, the phenomenon of capitalization would provide some protection for the interests of future generations. Decisions that lead to degradation of the local environment at some later date will be reflected in reduced current property values. Capitalization of future streams of benefits and costs can thus compel even myopic decision-makers to take cognizance of the future.

Appendix

In this appendix we explicitly incorporate a local public good into our median-voter model. Let z be per-capita consumption of the public good which the community purchases at a price p, and continue to let c be a composite private good which serves as the numeraire. Suppose, initially, that the community can finance the local public good with a combination of head taxes and taxes on capital. The first-order conditions for a welfare maximum in this problem require: (i) the community must set the tax rate on capital equal to zero and thus finance the public good entirely through the head tax; (ii) the marginal rate of substitution between α and c must equal f_α; and (iii) the marginal rate of substitution between z and c must equal p. The first two of these conditions are consistent with the discussion in section 2 of the paper; the third is not surprising.

Now suppose that we rule out the use of the head tax and require that the public good be financed entirely by taxing capital; this is, we require:

$$pz = tk. \tag{A.1}$$

The problem then becomes: maximize $u(c, z, \alpha)$ subject to the private budget constraint, the government budget constraint in (A.1), and the rate of return constraint in (2). Let γ_1, γ_2 and γ_3 be the Lagrange multipliers associated with these constraints. Then the first-order conditions for this problem require:

$$u_c = \gamma_1, \tag{A.2}$$

$$u_z = \gamma_2 p, \tag{A.3}$$

$$\gamma_2 t = -f_{kk}[\gamma_3 - \gamma_1 k], \tag{A.4}$$

$$\gamma_3 - \gamma_2 k = 0, \tag{A.5}$$

$$u_\alpha = -\gamma_1 f_\alpha - f_{k\alpha}[\gamma_3 - \gamma_1 k]. \tag{A.6}$$

Assuming the community chooses a positive level of z, t must be positive. Given that t is positive and f_{kk} is negative, (A.4) implies that $(\gamma_3 - \gamma_1 k)$ must be positive. If $(\gamma_3 - \gamma_1 k)$ is positive, then (A.5) requires that γ_2 must be greater than γ_1; (A.2) and (A.3) then imply that the marginal rate of substitution between the private good will exceed the price of the public good, i.e. the public good will be underprovided. This result is consistent with those in the Wilson (1986), Zodrow and Mieszkowski (1986), and Wildasin (1986) papers.

Combining the first-order conditions shows that the community will choose a level of environmental quality such that:

$$-u_\alpha/u_c = f_\alpha - t(f_{k\alpha}/f_{kk})(u_z/u_c)/p. \tag{A.7}$$

The community's marginal willingness-to-pay for better environmental quality is greater than f_α, and therefore the community sets an inefficiently low environmental standard. As in the simpler model presented in the text, the source of the inefficiency is the fiscal effect of environmental policy, $-t(f_{k\alpha}/f_{kk})$; the community relaxes standards in pursuit of greater tax revenues as well as higher wages.

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EFFICIENCY OF NON-COOPERATIVE EMISSION TAXES IN PERFECTLY COMPETITIVE MARKETS*

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With the current efforts to regulate the emissions of greenhouse gases and other cross border pollutants, the question of environmental federalism is as important as ever. By generalising the model presented by Oates and Schwab (1987, 1988), we show that the well established result within environmental federalism, that the government of a small country has no incentive to depart from the cooperative choice of environmental standards, does not hold for pollutants that have regional or global characteristics, as e.g. sulphur dioxide and carbon dioxide has. (JEL: H77, Q58)

1. Introduction

With the current efforts to cut the emission of greenhouse gases, the question of environmental federalism – the division of responsibility for environmental regulation between different levels of government – deserves as much attention as ever. Current implementations vary. In the EU, for example, the price of emitting CO_2 has been harmonised for major stationary emitters. However, in other areas of environmental management, there are still large differences within the EU. One of these fields is the level of support to renewable electricity sources. Within this field, cooperation attempts at the EU level have been short-lived due to fierce opposition they have been met by some member states.

Within environmental federalism, an important question is the efficiency of non-cooperative environmental standards. A well established result within the literature is that, in perfectly competitive markets, a small state has no incentive to depart from the cooperative choice of environmental standards as long as pollution generated in one jurisdiction doesn't spill over into another. Two of the first ones to show this formally were Oates and Schwab (1987, 1988). Our objective is to extend their analysis by allowing for regional, e.g. SO_2, and global pollutants, e.g. CO_2. Most previous work, both within the strand that assumes perfect and within the strand that assumes imperfect competition, only consider local pollutants. Cross-border pollutants are, in our opinion, underrepresented. Thus, our aim is to contribute to the strand of literature that deals with them. We acknowledge that our assumption of perfect competition, inherited from Oates and Schwab, is a crude simplification, but we hope that our analysis will serve as a starting point for more elaborate analyses.

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The paper is structured as follows. In Section 2, we review the main contributions within the field of environmental federalism. In Section 3, we outline the model and derive equilibrium conditions for the amount of capital employed and emissions generated by each state. In Section 4, we study some of the comparative statics of a unilateral emission tax increase. In Section 5 and 6, we derive the non-cooperative and co-operative choice of emission taxes, respectively. Section 7 concludes.

2. A brief literature review

Since the early papers of the 1970s and 1980s, among others Cumberland (1979, 1981) and Oates and Schwab (1987, 1988), the body of literature within environmental federalism has expanded along a number of different themes. Most importantly, with new insights on how to model imperfect competition, the literature has expanded to include markets where either producers or jurisdictions, or both, can affect prices.

A well established result within the strand that assumes perfect competition between the polluting firms is that a small country has no incentive to depart from the cooperative choice of environmental standards, assuming there are no pollution spillovers between states, see e.g. Rauscher (1994) or Ulph (1997). If trade policy is not banned, this result holds regardless of whether the countries are large or small, i.e. whether they can influence world prices or not. However, if trade policy is banned, the government of a large country may use environmental policy to improve its terms of trade. The government of a small country, however, has no incentive to depart from the cooperative equilibrium, because by assumption it cannot influence the country's terms of trade, and failure to internalise environmental externalities is welfare reducing.

The results within the strand of literature that assumes less than perfect competition between the polluting firms are less conclusive. Early work within this strand relies on oligopoly models in the tradition of Brander and Krugman (1983) and Brander and Spencer (1985), and assumes that firms are immobile. Relying on the Cournot duopoly presented by Brander and Spencer (1985), Barrett (1994) shows that in the absence of trade policy, governments will bid down each others' environmental standards to shift profits toward domestic producers. However, if firms compete in prices rather than quantities, they will bid up each others' standards. More recent work, originating from Markusen et al. (1995), assumes that firms are mobile. As with immobile firms, the finding of Markusen et al. is that without cooperation, governments will either bid up or down each others' emission taxes. However, the determining factor is not whether firms play Cournot or Stackelberg, but the disutility of pollution. If the disutility of pollution is large enough, the states will increase their emission taxes until the polluting firms are driven out of business.

Subsequent research has made additional simplifications, especially regarding transportation costs while relaxing others, such as the number of countries (Rauscher 1995) and the number of firms (Greaker 2003, Hoel 1997, Ulph and Valentini 2001). With exception of Rauscher, the results are in line with Markusen et al. Of the above mention analyses, Rauscher is the only who allows for pollution spillovers. He reports that the opportunity cost, in terms of environmental damages, of undercutting foreign environmental regulations becomes infinitesimally small if pollution is perfectly global.

Within the non-competitive strand, Pflüger (2001) pursues an alternative strategy, but as most of the previous research, assumes that pollution is strictly local. Relying on the model of monopolistic competition by Dixit and Stiglitz (1977), Pflüger shows that choice of emissions tax by one state imposes a number externalities on the other, both positive and negative. Non-cooperative taxes are lower than cooperative taxes if the importance of emissions in production, relative to labour, is small in comparison to transport costs and the mark-up on average variable costs. However, in contrast with the oligopoly model by Markusen et al. (1995), in Pflüger the disutility of pollution is not among the parameters that separate the non-cooperative choice from the cooperative choice.

3. Model outline

Following Oates and Schwab (1987, 1988), we analyse the choice of emission taxes, τ^i, in an assymmetric general equilibrium model of a federal economy of small states. The states are small in the sense that they cannot influence the rate of return to capital, R, and thus treat it as exogenous. In the spirit of the original model, we assume that capital and goods are perfectly mobile. Labour, in contrast, is perfectly immobile. Thus, the supply of labour is fixed in each state.

Emissions, E^i, are generated as a by-product in the manufacturing of a homogeneous private good. Besides emissions, production requires capital, K^i, and labour, L^i. Following Oates and Schwab, we assume that the good is manufactured by perfectly competitive firms with technologies that may vary across states, but all of which exhibit constant returns to scale with regard to the three inputs.

The property of constant returns to scale and the assumption of a fixed supply of labour allow us to write the production functions in per worker terms, $F^i\left(K^i,L^i,E^i\right)=L^i f^i\left(k^i,e^i\right)$. By partial derivation of it with respect to K^i, L^i and E^i, we obtain the marginal products of capital, labour, and emissions as

$$F^i_{K^i}(\cdot)=f^i_{k^i}(\cdot),$$

$$F^i_{L^i}(\cdot)=f^i(\cdot)-k^i f^i_{k^i}(\cdot)-e^i f^i_{e^i}(\cdot), \text{ and}$$

$$F^i_{E^i}(\cdot)=f^i_{e^i}(\cdot),$$

respectively, where subscripts denote partial derivatives. We assume that the marginal products of $f^i\left(k^i,e^i\right)$ are positive but diminishing, and that $f^i_{k^ie^i}(\cdot)>0$ and $f^i_{e^ik^i}(\cdot)>0$, i.e. that capital and emissions are q-compliments, using the definition by Seidman (1989).

As price takers, firms will employ capital up to the point where the marginal unit earns just enough to cover its cost. Thus, in equilibrium,

$$(1)\qquad f^i_{k^i}(\cdot)=R, \text{ for all states } i,$$

by choosing the private good as the numéraire. As with capital, firms choose a level of emissions which equates the marginal product of emission with the tax rate. Thus, in equilibrium,

$$(2)\qquad f^i_{e^i}(\cdot)=\tau^i, \text{ for all states } i.$$

We assume that within each state, workers are identical in both preferences and productive capacity, and that they are paid a wage equal to their marginal product. In addition to wages, workers receive tax income, $e^i\tau^i$, and exogenous income, b^i. For simplicity, we assume that all capital is owned by foreigners. With this simplification, we can write the budget constraint of the representative worker, resident of state i as

$$(3)\qquad x^i=f^i(\cdot)-k^i f^i_{k^i}(\cdot)-e^i f^i_{e^i}(\cdot)+e^i\tau^i+b^i,$$

where x^i is the consumption of the private good. Consumption of it increases utility $u^i=u^i\left(x^i,O^i\right)$, whereas exposure to pollution, O^i, reduces utility. We define the level of pollution as $O^i=O^i\left(e^1,...e^i,...,e^n\right)$, where the sign of the partial derivatives depend on the type of pollutant. We examine four distinct types of pollutants, shown in Table 1.

We distinguish here between two types of regional pollutants, those that affect the level of pollution both in the source state and in neighbouring states, and those that affect neighbour-

Table 1. Types of pollutants

Type of pollutant	Pollution function characteristics
Local	$O^i_{e^i}(\cdot)>0$, $O^i_{e^j}(\cdot)=0\ \forall j\neq i$
Regional and partially transboundary	$O^i_{e^j}(\cdot)>0\ \forall i,j$
Regional and perfectly transboundary	$O^i_{e^i}=0$, $O^i_{e^j}(\cdot)>0\ \exists j\neq i$
Global pollutant	$O^i_{e^i}(\cdot)=O^i_{e^j}(\cdot)>0\ \forall i,j$

ing states only. An example of the former is wastewater emissions is context of the Baltic Sea. An example of the latter is emissions of SO_2 that only affect neighbouring states.

4. Comparative statics of an unilateral emission tax change

Total differentiation of the equilibrium conditions (1) and (2) with respect to k^i, e^i and τ^i, yields the following system of equations

$$\begin{bmatrix} f^i_{k^ik^i}(\cdot) & f^i_{k^ie^i}(\cdot) \\ f^i_{e^ik^i}(\cdot) & f^i_{e^ie^i}(\cdot) \end{bmatrix} \begin{bmatrix} dk^i \\ de^i \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} d\tau^i.$$

From Cramer's rule, it follows that

$$\frac{dk^i}{d\tau^i} = \frac{-f^i_{k^ie^i}(\cdot)}{A} < 0 \quad \text{and that} \quad \frac{de^i}{d\tau^i} = \frac{f^i_{k^ik^i}(\cdot)}{A} < 0,$$

because $A = f^i_{k^ik^i}(\cdot) f^i_{e^ie^i}(\cdot) - f^i_{k^ie^i}(\cdot) f^i_{e^ik^i}(\cdot) > 0$, as we show in Appendix 1. Thus, increasing the tax rate reduces both the amount of capital employed and the amount emissions generated by a particular state.

5. Non-cooperative choice of emission taxes

Without coordination, national governments maximise the utility of the representative domestic consumer, u^i, subject to budget constraint in (3) and to the factor demands in (1) and (2). The Lagrangian for the non-cooperative maximisation problem can be written as

$$\begin{aligned} \Gamma \equiv\ & u^i\left(x^i, O^i\right) \\ & -\lambda\left[x^i - b^i - e^i\tau^i - f^i(\cdot) + k^i f^i_{k^i}(\cdot) + e^i f^i_{e^i}(\cdot)\right] \\ & -\gamma\left[f^i_{k^i}(\cdot) - R\right] \\ & -\eta\left[f^i_{e^i}(\cdot) - \tau^i\right] \end{aligned},$$

and the FOCs, with respect to x^i, e^i, k^i and τ^i, respectively, as

$$\lambda = u^i_{x^i}(\cdot),$$

(4) $$u^i_{O^i}(\cdot) O^i_{e^i}(\cdot) + \lambda\tau^i - \lambda k^i f^i_{k^ie^i}(\cdot) - \lambda e^i f^i_{e^ie^i}(\cdot) - \gamma f^i_{k^ie^i}(\cdot) - \eta f^i_{e^ie^i}(\cdot) = 0,$$

(5) $$-\lambda k^i f^i_{k^ik^i}(\cdot) - \lambda e^i f^i_{e^ik^i}(\cdot) - \gamma f^i_{k^ik^i}(\cdot) - \eta f^i_{e^ik^i}(\cdot) = 0, \text{ and}$$

(6) $$\eta = -\lambda e^i.$$

By substituting (6) into (5), we obtain $\gamma = -\lambda k^i$. By substituting this and the expressions for the two other Lagrange multipliers into (4) yield

(7) $$\tau^i = -\frac{u^i_{O^i}(\cdot) O^i_{e^i}(\cdot)}{u^i_{x^i}(\cdot)}.$$

Equation (7) says that, without cooperation, national governments set a tax equal to marginal social damage to domestic workers. The damage is measured in terms of the willingness to sacrifice consumption in return for a decrease in the level of pollution.

6. Cooperative choice of emission taxes

Through cooperation, the welfare of neighbouring states is taken into consideration when deciding on the level of emission tax. Thus, the constraints are the same as in the non-cooperative case with one addition, the constraint of not reducing welfare abroad below a certain level. Here, this level is given by $\bar{u}^s$. The additional constraint captures the effect of decisions in one state on the welfare in other states. With these changes, the Lagrangian for the cooperative maximisation problem can be written as

$$\begin{aligned} \Lambda \equiv\ & u^i\left(x^i, O^i\right) \\ & -\lambda\left[x^i - b^i - e^i\tau^i - f^i(\cdot) + k^i f^i_{k^i}(\cdot) + e^i f^i_{e^i}(\cdot)\right] \\ & -\gamma\left[f^i_{k^i}(\cdot) - R\right] \\ & -\eta\left[f^i_{e^i}(\cdot) - \tau^i\right] \\ & -\sum_{\substack{s=1 \\ s\neq i}}^{n} \xi^s\left[\bar{u}^s - u^s\left(x^s, O^s\right)\right] \end{aligned}.$$

Since $\xi^s = -\partial\Lambda / \partial\hat{u}^s$, we can interpret ξ^s as the shadow prices, measured in units of u^i, that domestic consumers must to pay to increase utility abroad. $\partial\Lambda / \partial\hat{u}^s \leq 0$ because the only way for domestic consumers to improve welfare abroad is by reducing emissions. Assuming that the domestic level of emissions is optimal, reducing them further cannot be welfare improving. It follows that $\xi^s \geq 0$.

The FOCs, with respect to x^i, e^i, k^i and τ^i, respectively, can be written as

$$\lambda = u^i_{x^i}(\cdot),$$

$$u^i_{O^i}(\cdot)O^i_{e^i}(\cdot) + \lambda\tau^i - \lambda k^i f^i_{ke^i}(\cdot) - \lambda e^i f^i_{e^ie^i}(\cdot)$$

$$-\gamma f^i_{k^ie^i}(\cdot) - \eta f^i_{e^ie^i}(\cdot) + \sum_{\substack{s=1 \\ s\neq i}}^{n} \xi^s u^s_{O^s}(x^s, O^s) \cdot O^s_{e^i}(\cdot) = 0$$

$$-\lambda k^i f^i_{kk^i}(\cdot) - \lambda e^i f^i_{ek^i}(\cdot) - \gamma f^i_{kk^i}(\cdot) - \eta f^i_{ek^i}(\cdot) = 0,$$

and $\eta = -\lambda e^i$.

By performing the same substitutions as in the non-cooperative case, we obtain

$$\text{(8)} \quad \tau^i = -u^i_{O^i}(\cdot)O^i_{e^i}(\cdot)/u^i_{x^i}(\cdot) - \sum_{\substack{s=1 \\ s\neq i}}^{n} \xi^s u^s_{O^s}(x^s, O^s) \cdot O^s_{e^i}(\cdot)/u^i_{x^i}(\cdot).$$

The difference between the cooperative and non-cooperative tax level, (8) and (7), respectively, is

$$-\sum_{\substack{s=1 \\ s\neq i}}^{n} \xi^s u^s_{O^s}(x^s, O^s) \cdot O^s_{e^i}(\cdot)/u^i_{x^i}(\cdot),$$

which represents the negative trans-state externality in our model, i.e. the effect of domestic emission on the level of pollution, and welfare, abroad. For regional and global pollutants, the term is larger than zero, because there is a state abroad for which $O^s_{e^i}(\cdot) > 0$. It follows, that for regional and global pollutants, the non-cooperative level of emission taxes is inefficiently low. For local pollutants, the term is zero, because $O^s_{e^i}(\cdot) = 0$ for all states s abroad. It follows, that for local pollutants, the non-cooperative level of emission taxes is efficient.

Regional pollutants that are perfectly trans-boundary, e.g. emission of SO_2 that only affect neighbouring states, illustrates nicely the lack of incentives. The domestic government has no incentive to regulate them since the damage is borne entirely by neighbouring states. Thus, the domestic government chooses a zero tax rate. Obviously, this is inefficient.

7. *Discussion and policy implications*

The inefficiency arises because national governments, by assumption, care only for costs and benefits that accrue to domestic consumers; the utility from more consumption accrue in full to domestic workers, whereas the disutility from more pollution is borne only partially by domestic consumers. The only way to internalise the pollution externality, and remove the inefficiency, is by cooperation. Thus, our recommendation is that that the regulation of regional and global pollutants, or the activities that cause them, such as the use of fossil fuels in electricity generation and the associated generation of CO_2 and SO_2, should be coordinated at the federal level.

Appendix 1

The per-worker profit of a firm producing in state i is given by $f^i\left(k^i, e^i\right) - Rk^i - \tau^i e^i$. The FOCs of the firm's problem are $f^i_{k^i}(\cdot) - R = 0$ and $f^i_{e^i}(\cdot) - \tau^i = 0$. The SOCs is that the Hessian,

$$H = \begin{bmatrix} f^i_{k^ik^i}(\cdot) & f^i_{k^ie^i}(\cdot) \\ f^i_{e^ik^i}(\cdot) & f^i_{e^ie^i}(\cdot) \end{bmatrix},$$

is negative definite. For negative definiteness, the leading principal minors must alternate in sign, with the first leading principal minor being negative, i.e. $f^i_{k^ik^i}(\cdot) < 0$ and $f^i_{k^ik^i}(\cdot) f^i_{e^ie^i}(\cdot) - f^i_{k^ie^i}(\cdot) f^i_{e^ik^i}(\cdot) > 0$.

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