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The Impact of Climate Change and Climate Policy on the Canadian Economy

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1 Introduction

The emerging scientific consensus that the global climate is changing has sparked substantial debate over both the impact and effectiveness of policy targeted at mitigating greenhouse gas emissions (see e.g. Stern (2006) and Nordhaus (2008)). In this paper, we seek to quantify the net economic impact of climate change and climate change policy on the Canadian economy. In particular, we seek to quantify the economic costs and benefits from different emission reduction targets on the Canadian economy, and how this compares with the average economic impact in the rest of the world economy.

To tackle these questions, we combine a small open economy model of Canada with the ANEMI model. The ANEMI model is an integrated assessment model developed at Western University that incorporates an energy sector as well as fossil fuel production into a neoclassical growth model. We use the ANEMI framework to both develop our baseline analysis of the impact of carbon taxes on the world economy, and to generate a path of carbon emissions, climate, and (relative) price of fossil fuels which we feed into our small open economy model of Canada.[1]

The ANEMI model incorporates several key innovations that are absent from the influential DICE framework of Nordhaus (2008). First, the ANEMI model includes an explicit energy sector which produces a composite energy good used in the production of final output. This energy intermediate good is in turn

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[1]As a small economy, the direct impact of changes in Canadian greenhouse gas emissions on the level of global greenhouse stocks is relatively small, since Canada accounts for less than 3 percent of global GHG emissions This leads us to take the path of global greenhouse gas stocks as independent of Canadian emissions.

produced using a composite of two broad energy sub-composites: heat energy (i.e. fuel energy burned for transportation or industrial purposes) and electrical energy. Each of these energy types is produced using different technologies for each of the major energy sources. This structure provides a useful midpoint between aggregate models (such as DICE) which abstract from detailed modeling of energy and more detailed bottom up models which typically abstract from key features of dynamics and optimal choice. The second innovation on the climate side is the inclusion of a simple production structure for fossil fuels. As a result, the path of fossil fuels evolves endogenously in the model, so that climate policy (such as carbon taxes which seek to lower demand for fossil fuels) and the negative impact of climate change on aggregate productivity (which tends to lower energy demand) both impact the temporal path of fossil fuel prices. In turn, the equilibrium prices of fossil fuels impact investment in capital stocks to produce energy using different types of fossil fuels.

To highlight how Canada differs from the global average, we compare the results from our Canadian economy to those of the ANEMI model for a carbon tax designed to maintain the level of CO2e below 550 ppm. We find that the economic benefits to Canada of this carbon tax are much smaller (in fact, negative) than they are for the rest of the world. This finding is mainly due to large differences in the calibrated damage function in the Canadian and world model ANEMI economies. These differences reflect significant differences in estimated impact of small temperature increases on the Canadian and global economies. In addition, our benchmark simulation results highlight the large impacts that carbon taxes can have on long run shifts in fossil fuel prices by shifting the temporal path of consumption.

There is a large and growing literature that seeks to quantify the economic impact of climate change as well as the costs of lowering greenhouse gas emissions (e.g. see Stern (2006) and Nordhaus (2008)). While our modeling structure builds upon the heavily cited DICE model of Nordhaus, the ANEMI model differs in how we model the energy sector.

Most of the literature with a Canadian focus has used static CGE models used to examine the impacts of climate policy on Canada (see e.g. Hamilton and Cameron (1994), Jaccard and Montgomery (1996), Ab Iorwerth et al. (2010), Dissou (2005), Wigle and Snoddon (2007), Boehringer and Rutherford (2010). Several papers have also used sectoral models: Jaccard and Montgomery (1996), Jaccard et al. (2003), Simpson et al. (2007). Our model differs both in the details of how we model the interaction between energy and economic output, and in our focus on comparing the net economic benefits of climate policy in Canada versus the rest of the world.

The remainder of this paper is organized as follows. Section 2 describes the calibration of the Canadian damage function. Section 3 outlines the key features of the model, while Section 4 reviews the calibration of key model parameters and the baseline simulation. Section 5 discusses our carbon tax experiment, while Section 6 provides a brief conclusion.

2 A Canadian Climate Damage Function

A key element in assessing the impact of climate change and climate policy in Canada is the economic damages associated with changes in mean temperature. This is especially important when comparing Canada to global averages, given our geographical location.

In constructing a climate change damage function, we adopt the approach of Nordhaus (2008) and model damages as a quadratic in global mean temperature. To construct estimates for Canada, we draw on regional damage estimates for the U.S. from Mendelsohn (2001). Mendelsohn presents estimated damages for seven U.S. regions for five sectors (Agriculture, Forestry, Energy, Coastal Structures, and Water Resources) at varying degrees of warming (1.5, 2.5, and 5.0 degrees Celsius) and varying levels of precipitation (0%, 7%, and 15% over 1990 levels) in 2060. We fit these estimates to our quadratic using estimated damages at $T = 2.5°$ and $T = 5°$ warming and 0% increase in precipitation above preindustrial levels for the four northern U.S. regions.

Figure 1 plots the U.S. regions for which Mendelsohn reports detailed estimates of the potential impact of climate change, and Table 1 summarizes the mapping we follow between U.S. regions and Canadian regions.

Table 1: Mapping U.S. Regions into Canadian Regions

Canadian Region	U.S. Region
Atlantic	North-East
Quebec	North-East
Ontario	North-East, Mid-West
Prairies	Northern Plains
B.C.	Pacific North-West

Figure 1: Mendelsohn's Regions

Source: Mendelsohn (2001, p. 8)

The estimates in Mendelsohn (2001) are based on studies employing both simulation models and empirical models examining cross-sectional differences across climate zones. The climate damages (benefits) are estimated separately for each sector and region, relative to a baseline scenario of the economic conditions in 2060.

Tables 2 and 3 show estimated market damages from Mendelsohn at 0% increase in precipitation.[2] At 2.5 degrees of warming all regions are experiencing net benefits in the Agriculture, Forestry, and Energy sectors, except for the Northwest region, which have damages of 0.6 billion. Damages to coastal structures are negligible, but the water systems sector see some damages, particularly in the Northwest region. Overall, the Northeast, Midwest, and Northern Plains regions have net benefits as a result of a 2.5 degree warming, whereas the Northwest region experience small damages.

At 5 degrees of warming the impact is more pronounced. The energy sector

[2] Appendix B: provides a comparison of the 7% and 15% precipitation scenarios.

now experiences damages in three regions, and the damages to the water sector are higher. The total impact from warming is still positive in three regions, though the benefits have declined compared to the 2.5 degree estimates.

Table 2: Mendelsohn's Damage Estimates for $T = 2.5°$ Warming

	Agriculture	Forestry	Energy	Coast	Water	Total
Northeast	2.8	2.6	0.2	-0.1	0.0	5.5
Midwest	6.3	1.0	0.3	0.0	-0.2	7.4
Northern Plains	4.3	0.5	0.1	0.0	-0.6	4.4
Northwest	2.1	-0.6	1.4	0.0	-3.2	-0.3

Note: Estimated regional impacts of climate change in 2060 (billions of 1998 USD/year). Coastal damages assumes 67 cm of sea level rise in 2.5 degree scenario. Impacts are beneficial if positive, harmful if negative.

Table 3: Mendelsohn's Damage Estimates for $T = 5°$ Warming

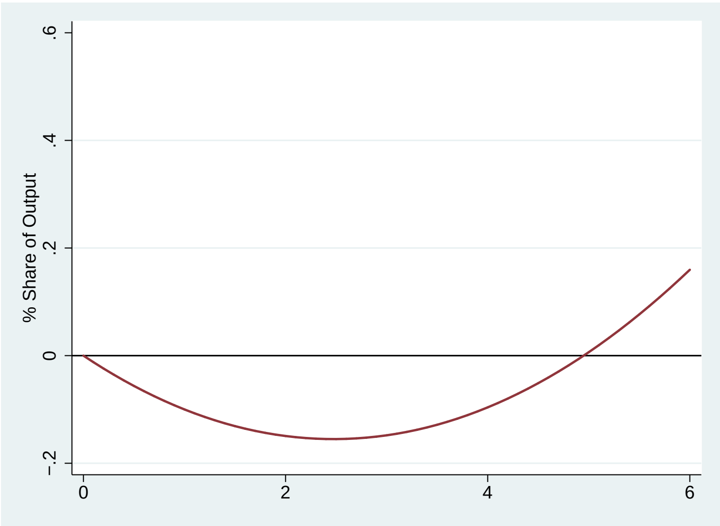
	Agriculture	Forestry	Energy	Coast	Water	Total
Northeast	1.8	2.6	-2.6	-0.2	-0.1	1.6
Midwest	3.6	1.0	-1.6	0.0	-0.5	2.4
Northern Plains	2.7	0.5	-1.2	0.0	-1.2	0.8
Northwest	1.7	-0.6	1.6	0.0	-5.7	-3.1

Note: Estimated regional impacts of climate change in 2060 (billions of 1998 USD/year). Coastal damages assumes 100 cm of sea level rise in 5.0 degree scenario. Impacts are beneficial if positive, harmful if negative.

Figure 2 plots the calibrated damage function. Damages are measured on the vertical axis as a share of output, and the horizontal axis shows the average increase in degrees Celsius relative to the base year. It is worth noting that we find economic benefits for low to moderate changes, and damages only for larger increases in Canadian temperatures.

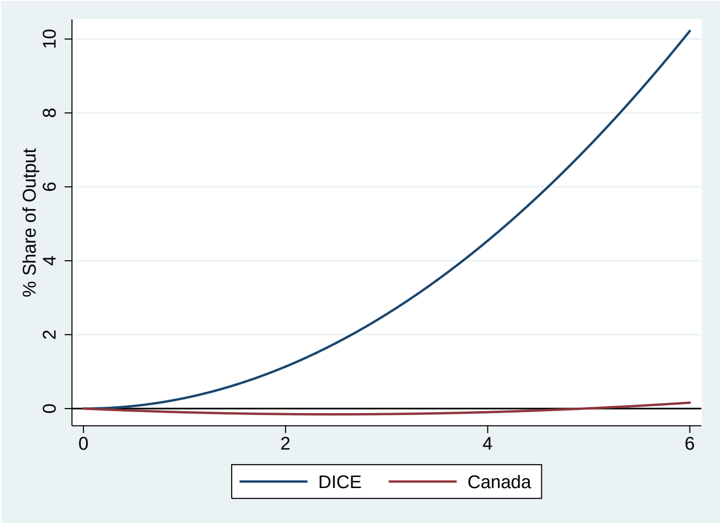
This is very different from the global average used in Nordhaus (2008), as can be seen from Figure 3 which plots both our calibrated damage function and that used in Nordhaus. However, Nordhaus takes into account damages to market sectors, as well as damages from increased incidence of catastrophic events, and damages to health, human settlements, and ecosystems. The estimates from Mendelsohn do not take into account catastrophic events, and damages to health and ecosystems. Therefore, it may be that the Canadian damage

Figure 2: Calibrated Damage Function for Canada



Note: x-axis displays increase in degrees Celsius over base year. Economic damages are positive, benefits negative.

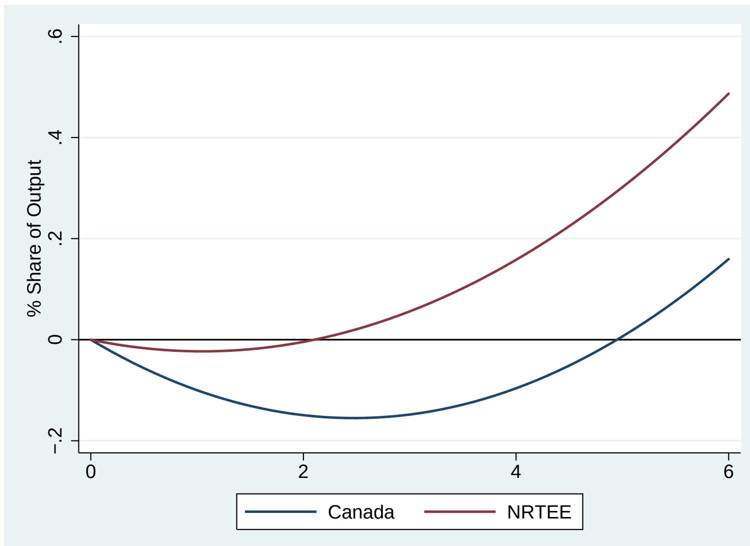
Figure 3: Climate Damage Functions: Canada vs. the World



Note: x-axis displays increase in degrees Celsius over base year. Economic damages are positive, benefits negative.

function in Figure 2 reflects a lower bound, and that Canadian damages from warming are higher.[3]

Figure 4: Damage Function for Canada: NRTEE Forestry Estimates



Note: x-axis displays increase in degrees Celsius over base year. Economic damages are positive, benefits negative.

As Canada lies to the north of the U.S., the market benefits to Canadian Agriculture and Forestry may be higher than for the U.S. regions. However, in a recent report, the Canadian National Roundtable on the Environment and the Economy suggested that the Canadian Forestry sector may actually experience damages from warming (NRTEE, 2011). Figure 4 shows the Canadian damage function re-estimated using the Canadian climate damage estimates from the Roundtable.[4] The initial benefits from warming are much smaller for the NRTEE damage function, but the climate damages are still small compared to the global average.

[3]Appendix A: add catastrophic events into the damage function, following Nordhaus and Boyer (2000).

[4]Appendix C: provides a description of the NRTEE forestry damage estimates.

3 The Model

The model is based on ANEMI, an integrated assessment model developed at Western University. We model Canada as a small open economy that takes energy prices and the global stock of atmospheric carbon as given. That is, fossil fuel prices and the global mean temperature are endogenous variables in the ROW region, but exogenous to the Canadian energy economy. The paths for both of these variables (energy prices and temperature) are taken from simulations of the global version of the ANEMI model.[5]

The world energy-economy model extends the neoclassical (Solow) growth model to include an energy sector as well as the production of fossil fuels. A key feature of the model is the endogenous allocation of energy production across fossil fuels, hydro, nuclear, and alternative energy sources. This results in industrial green house emissions responding endogenously to both carbon taxes and to shifts in the relative prices of fossil fuels.

Figure 5 outlines the causal structure diagram for the energy economy-sector. In the model, the energy-economy sector takes Canadian mean temperature and population as inputs, as well as an exogenously specified path for fossil fuel endowments and the technology available to produce nuclear, hydro, and alternative energy. The climate damage relationship (which is a function of temperature) is similar to that of Nordhaus and Boyer (2000), and is represented by a quadratic function in global mean temperature.

The energy-economy sector produces the final consumption/investment good as well as industrial emissions. Industrial emissions are calculated from the burning of fossil fuels in producing energy services. Gross domestic product is equal to final output, and depends on the world's capital stock, labour force, and energy resources.[6] We assume that aggregate investment is equal to a fraction s of output.

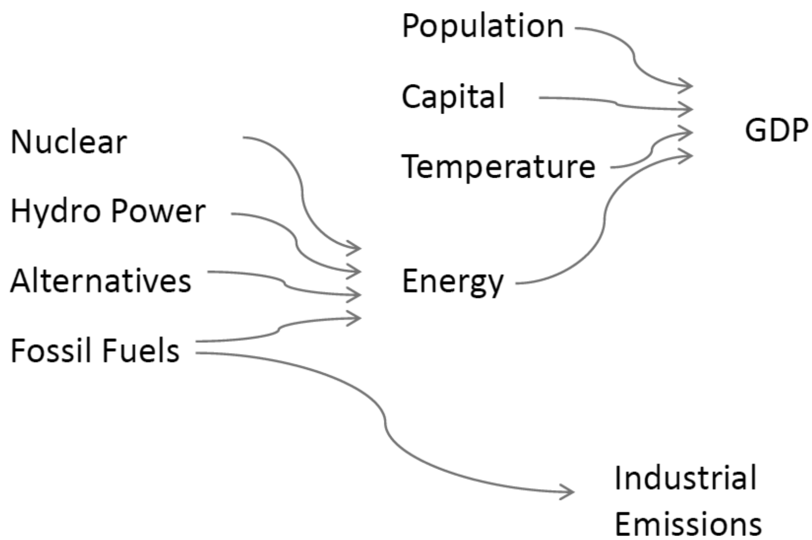
'Energy services' used in the production of the final good is a composite good aggregated from heat energy and electric energy. Heat energy is produced from fossil fuels and alternative energy sources. Electric energy is produced from fossil fuels, nuclear, and hydro power.

The production of output is negatively affected by climate damages. The global mean temperature represents a negative feedback to the economic system from industrial emissions through climate damages.

[5]A complete description of the global ANEMI model is available in Akhtar (2011).

[6]Note that energy production in the model is an intermediate good.

Figure 5: Causal Diagram for Energy-Economy Sector



3.1 Government

Climate policies are implemented by a government. The government can implement carbon taxes on energy consumption, and rebates these tax revenues lump-sum to the household. We assume a set of fuel specific taxes, τ_i, which depend on the emission intensity of each fuel type i. Finally, $\overline{T}$ is the sum of tax revenues from carbon. Then, $P_E E - \overline{T}$ is the household's income from selling energy services to the firm net of taxes.

3.2 The Representative Household

The model economy is populated by a stand-in household. The household has preferences over an aggregate consumption good, which can be represented by the utility function:

$$U(C) = ln(C) \tag{1}$$

where C is the final consumption good. The household supplies labour, L, inelastically to the market. We assume that the household owns the world's capital stock and natural resources. Thus, the consumer rents the capital to the firm, earning income rK, where r is the interest rate and K is the aggregate capital stock in the economy. The consumer also sells energy services to the firm, earning income $P_E E - \overline{T}$, where E is aggregate energy services, and P_E is the price of aggregate energy services. Given prices, the household maximizes utility subject to its budget constraint:

$$rK + wL + P_E E - \overline{T} \geq C + I \tag{2}$$

where government transfers are given by:

$$\overline{T} = \sum_i \tau_i F_i \tag{3}$$

Note that since the price of energy services P_E is a final price, it includes the effect of taxes on intermediate fossil fuels. Hence, one has to subtract the value of taxes from household income.

Investment, I, is assumed to follow a Solow investment rule where a fraction s of output, Y, is invested into new capital each period:

$$I = sY \tag{4}$$

3.3 Final Good Production

Production of final output is represented by a stand-in firm which employs a CES production technology. The firm hires labour, capital, and energy services from the stand in household and produces the final consumption/investment good. The aggregate production function is:

$$Y = \Omega A \left(\omega (K^\alpha L^{(1-\alpha)})^\gamma + (1-\omega) E^\gamma \right)^{\frac{1}{\gamma}} \tag{5}$$

where A is total factor productivity (TFP), and $1/(1-\gamma)$ is the elasticity of substitution between value added and the energy composite. We follow Nordhaus (2008), and model the damage coefficient, Ω, as a function of, T, global mean temperature:

$$\Omega = \frac{1}{1 + \theta_1 T + \theta_2 T^2} \tag{6}$$

3.4 Energy Production

Aggregate energy services, E, is modeled as a composite good produced from heat energy and electric energy:

$$E = \left(\lambda E_H^{\theta} + (1-\lambda)E_{El}^{\theta}\right)^{\frac{1}{\theta}} \tag{7}$$

Here, E_H is total heat energy produced, and E_{El} is total electricity produced. The elasticity of substitution is determined by the parameter θ, and λ is the CES share parameter.

3.5 Electric Energy Production

Electric energy is produced from fossil fuels, nuclear and hydro power. Nuclear and hydro power are assumed to follow an exogenous path, as both depend heavily on policy and regulatory decisions. Each period, the representative firm solves the following problem:

$$\min_{F_{El,i}} ATC_{El}\left(F_{El,Coal}, F_{El,Oil}, F_{El,Nat.Gas}\right) \quad s.t. \tag{8}$$

$$E_{El} \geq \overline{E}_{El}$$

$$P_{El} = ATC_{El}$$

$$K_{Coal},\ K_{Oil},\ K_{Nat.Gas} \quad \text{given.}$$

where

$$E_{El} = A_{El}\left(\alpha_1 F_{El,Coal}^{\vartheta} + \alpha_2 F_{El,Oil}^{\vartheta} + \alpha_3 F_{El,Nat.Gas.}^{\vartheta} + \alpha_4 \overline{F}_{El,Nucl.}^{\vartheta} + \alpha_5 \overline{F}_{Hydro.}^{\vartheta}\right)^{\frac{1}{\vartheta}} \tag{9}$$

and

$$a_i = \left(\frac{1}{\omega}\right)\left(g_i - \left(\frac{F_{El,i}}{K_i}\right)^2\right), \text{ for } i = 1, 2, 3. \tag{10}$$

That is, given the capital stocks for fossil fuels and the nuclear and hydro power available, the representative firm chooses $F_{El,Coal}$, $F_{El,Oil}$, and $F_{El,Nat.Gas}$

to minimize the average total cost of electricity. Here, A_{El} is a productivity term specific to electricity production, $F_{El,i}$ is the fuel input used for fuel type i in electricity production, and ϑ is the CES elasticity parameter.

The functions α_i, for the fossil fuels, are decreasing in the fuel-to-capital ratio. Inside a period this assumption implies diminishing returns, as capital is a fixed factor. The parameters a_4 and a_5 are fixed. The parameters ω and g_i are used to calibrate the relative levels of fossil fuels in electricity production.

3.6 Heat Energy Production

The structure for production of heat energy is symmetric to the production of electric energy. We assume that heat energy is produced from fossil fuels and alternative energy sources. Each period the representative firm solves the following problem:

$$\min_{F_{H,i}} ATC_H \left(F_{H,Coal}, F_{H,Oil}, F_{H,Nat.Gas}, F_{H,Alt.}\right) \quad s.t. \tag{11}$$

$$E_H \geq \overline{E}_H$$

$$P_H = ATC_H$$

where

$$E_H = A_H \left(\beta_1 F_{H,Coal}^{\vartheta} + \beta_2 F_{H,Oil}^{\vartheta} + \beta_3 F_{H,Nat.Gas.}^{\vartheta} + \beta_4 F_{El,Alt.}^{\vartheta}\right)^{\frac{1}{\vartheta}} \tag{12}$$

There is no capital in the heat energy sector. The capital for heat energy comprises part of the aggregate capital for the economy. The firm chooses $F_{H,Coal}$, $F_{H,Oil}$, $F_{H,Nat.Gas}$, and $F_{H,Alt.}$ to minimize the average total cost of heat energy. Here, A_H is a productivity term specific to heat energy production, $F_{H,i}$ is the input of fuel type i for heat energy production, β_i is the CES weight for fuel type i, and ϑ pins down the elasticity of substitution.

3.7 Fossil Fuel Price Functions

The fossil fuel price functions are increasing in the ratio of the reserve value at its base year relative to its current value.

$$P_{F_{i,t}} = \tau_{i,t} + P_{F_{i,t=1980}} \left(\frac{R_{i,t} + D_{i,t} - F_{El_{i,t}} - F_{H_{i,t}}}{R_{i,t=1980}} \right)^{\frac{1}{\rho}} \tag{13}$$

Here, subscripts i and t refer to the fossil fuel type and the year respectively. $P_{F_{i,t}}$ is the fuel price, $\tau_{i,t}$ is the fuel specific carbon tax, $P_{F_{i,t=1980}}$ is the price of fuel at the base year , $R_{i,t}$ is the current reserve level, $R_{i,t=1980}$, is the base year reserve level, and $D_{i,t}$ is the new discovery value. $F_{El_{i,t}}$ and $F_{H_{i,t}}$ is extraction of fuel for electricity and heat energy production respectively.[7] $\rho < 0$ is an elasticity parameter.

This specification includes two key channels which impact the extraction cost of fuel. First, the model assumes that marginal extraction costs increase as the current reserves ($R_{i,t}$) falls relative to the base year. That is, higher levels of extraction results in higher future prices. This upward pressure on prices can be offset by new discoveries, which are assumed to have lower marginal extraction costs than remaining stocks of known reserves. The paths for new fossil fuel discoveries are taken as exogenous in the model.

3.8 Alternative Heat Energy Price Function

The price of alternative heat energy is represented by the function:

$$P_{F_{Alt.,t}} = \mu_{1,t} + F_{H_{Alt.,t}}^{\mu_{2,t}} \tag{14}$$

$P_{F_{Alt.,t}}$ is the price, and $F_{H_{Alt.,t}}$ is the quantity of alternative fuel used in heat energy production. $\mu_{1,t}$ and $\mu_{2,t}$ are parameters. We assume that they are decreasing, representing that the price alternative fuel is falling over time.

3.9 Extraction and Trade in Fossil Fuels

The structure for the production of energy in the regional model is the same as in the global ANEMI model. However, since the prices of fossil fuels are exogenous, there is no mechanism to clear the market for fossil fuels in the regional energy economy. Demand and supply is determined separately. If supply is greater than demand, the excess supply is exported. Vice versa, the excess demand is met with imports. Extraction decision in the Canadian energy economy depends on the fossil fuel price, and are given by the inverse of the price functions:

[7] For the calibration we have chosen 1980 as our base year.

$$F_{TE,i,t} = R_{i,t} + D_{i,t} - R_{i,t=1980}\left(\frac{\nu_i + \overline{P}_{F_{i,t}}}{P_{F_{i,t=1980}}}\right)^{\frac{1}{\rho}} \tag{15}$$

Here, $F_{TE,i}$ is the total extraction of fossil fuel type i at time t, given the current world price $\overline{P}_{F_{i,t}}$. $R_{i,t}$ is the current reserve value, $R_{i,t=1980}$ is the reserve value at the base year, $D_{i,t}$ is new discoveries, and $P_{F_{i,t=1980}}$ is the world price of fossil fuel i at the base year. ρ is an elasticity parameter, and ν_i is a calibration parameter adjusting the level of extraction.

Given the exogenous world price, demand for fossil fuels in the regional model is given. We assume that net exports of fossil fuel i, $NX_{i,t}$, is the difference between demand and total extraction each period. That is, net exports of fossil fuel type i is equal to total extraction minus fuel used for the production of heat energy and electric energy:

$$NX_{i,t} = F_{TE,i,t} - F_{H,i,t} - F_{El,i,t} \tag{16}$$

3.10 Energy Demand

In the model, final energy demand is from the final good producer. We assume that the final good producer is competitive, and takes the price of the energy composite as given when deciding how much to purchase. Thus, we solve for the equilibrium price within each period such that final energy demand equals final energy supply. At period t, capital and labour inputs are fixed. At period t, capital and labour inputs are fixed. Thus, equilibrium demand for aggregate energy services can be expressed as:

$$E = \left(\frac{(1-\alpha-\beta)AK^{\alpha}L^{\beta}}{P_E}\right)^{\frac{1}{(\alpha+\beta)}} \tag{17}$$

E is the representative firm's demand for aggregate energy services, K is aggregate capital, L is the world's labour force, and P_E is the price of aggregate energy services. α and β are the share parameters from the aggregate production function.

3.11 Investment in Capital for Electricity Production

The available supply of investment funds for electricity production is assumed to follow a Solow rule. That is, each period I_{El} is available to invest in new electricity capital:

$$I_{El} = sY \left(\frac{\sum_i K_i}{K + \sum_i K_i} \right) \tag{18}$$

Here K_i is the current capital stock used to produce electricity from energy source i, which could be either a fossil fuel, nuclear or hydro power. K without a subscript i is the aggregate capital stock for the economy.

Investment into new capital for electricity production follows an average cost investment rule and is allocated by a built-in Vensim function called 'Allocate-by-priority'. For investment into electricity capital in the energy sector, the allocate-by-priority (ABP) function serves the purpose of a market clearing mechanism. The ABP function in Vensim is based on the Wood algorithm for allocating a resource in scarce supply to competing orders or 'requests'.[8] The ABP function takes as inputs the supply of available investment funds to be allocated, and the 'capacity' and the 'priority' of each order, representing the size and competitiveness of the orders respectively.

As explained above, given the fixed quantity of investment funds available inside a period, the market allocation depends on the size of the request and relative priority given to each sector, and the width parameter. After testing multiple approaches we decided to set the priorities for the sectors equal to each other, and only focus on the request dimension. The intention behind this decision is to simplify the calibration and to make the investment function more transparent.

3.12 Average Cost Investment Rule

The demand for new investment funds for each energy source used in electricity production is based on an average cost investment rule where the allocation is determined by the ABP function. Given a fixed priority across energy sources, the 'request' function takes the following form:

$$Req_i = \varphi_i \delta_i K_i + \left(\frac{K_i}{\sum_i K_i} \right) \left(\frac{ATC_{El}}{ATC_i} \right) \tag{19}$$

The request for new investment funds is a function of "replacement capital" and the current capital share of the sector scaled by its relative average total cost. Each period a share δ of existing capital depreciates, and we assume that all sectors will ask for that capital to be replaced. The parameter φ is a weighting

[8]The Wood algorithm was invented by William T. Wood.

factor that will reduce the request for replacement capital if the average total cost exceeds some threshold value. The second term is the relative size of the current capital stock for energy source i multiplied by its relative average cost. This implies that sectors with a lower average cost will have higher requests. ATC_{El} is the average total cost of electricity, and ATC_i is the average total cost of energy source i.

Since the path for nuclear and hydro power is exogenous, the capital stock used in production of nuclear and hydro power is also prescribed. The amount needed for new capital for nuclear and hydro power is subtracted from the total available for investment into electricity capital; what is left over is allocated to the fossil fuel capital stocks using the ABP function.

4 Calibration of Energy Economy

To calibrate the model, we choose parameters to match the level and trend in energy consumption, industrial emissions of GHGs, and economic activity from 1980 to 2005. Historical energy data was collected from the Energy Information Administration (EIA), the World Bank's World Development Indicators (WDI), and Statistics Canada.

4.1 Calibration Strategy

We calibrate the model in two steps. First, we choose initial conditions, exogenous variables, and parameters. Given those assumption, we calibrate the energy sector of the model to match fossil fuel consumption for the period 1980-2005.

For each year in the calibration period we solve a system of equations where $\{g_i, \beta_i\}_{i=1,2,3}$ is chosen to minimize the distance between fossil fuel consumption in the model and the historical trend lines in the data.

The g_i are parameters from the functional forms for the CES-weights in electricity production function (equation 10), and the β_i are the CES-weights in the heat energy production function (equation 12). For the calibration period we solve for these six parameters as part of the non-linear system of equations that make up the energy economy. The calibration targets are the observed trend lines of fossil fuel consumption in heat energy and electricity production.

The calibration implies the relative quantities of fossil fuels used in production of energy. Given these values, the productivity parameters are chosen so as to match the levels of energy and economic output for the calibration period.

For 2006 and after, $\{g_i, \beta_i\}_{i=1,2,3}$ is extrapolated following a nave updating rule, where

$$x_{i,t+1} = x_{i,t} \left(1 + \nu_i \left(\frac{x_{i,t} - x_{i,t-1}}{x_{i,t-1}}\right)\right) \tag{20}$$

The set of parameters $\{\nu_i\}$ are chosen to minimize the change in the trend for each of the fossil fuels in the period immediately following the calibration stage.

4.2 Calibration of Global Model

The energy data for the global energy economy is from the U.S. Energy Information Administration (EIA) and the World Bank's World Development Indicators (WDI). From the EIA we collected data on fossil fuel reserves, fossil fuel discoveries, total energy produced from fossil fuels, and total electricity produced from nuclear and hydro power. From WDI we collected data on the production of electricity from fossil fuels.

Energy stock variables are denoted in Gigajoules (GJ) and energy flow variables are denoted in GJ/year. The energy stock variables are the fossil fuel reserves. The flow variables are fossil fuel discoveries, fossil fuel inputs into production of heat and electric energy, alternative energy input into heat energy production, and nuclear and hydro power used to produce electricity. We use conversion factors from the EIA to convert cubic feet of natural gas, short tons of coal, and barrels of oil into GJ of energy.[9]

4.3 Fossil Fuel Reserves and Discoveries

A key factor in our simulations is the projected path for future discovery of fossil fuels in Canada.

The Canadian oil sands are a vast resource; however, economical, political, and technological constraints make it very difficult to make a prediction about what share of the oil sands will actually be extracted. Given these constraints, we assume here that the total recoverable oil in Canada is about 410 billion barrels. That is approximately 25% of the oil estimated to be in the Alberta oil sands. In 2007, the Alberta Energy and Utilities Board estimated that about

[9] 1cubic foot of natural gas = 0.001.0846 GJ, 1short ton of coal = 21.279 GJ, and 1 barrel of oil = 6.119 GJ.

10% of the oil was recoverable given the economic conditions and technology available at that time.

For simplicity, we assume that future fossil fuel discoveries are known at the beginning of time. Thus, the initial model reserves are the sum of expected discoveries and the reported reserves in the base year. Thus, the initial reserves used in the model (column 1) are equal to the sum of the remaining three columns in in Table 4 below.

Table 4: Fossil Fuel Reserves

Fuel Type (Billion GJ)	1980 Assumed Initial Reserves Model	1980 (EIA & Stat. Canada)	1980 - 2005 Disc. (EIA & Stat. Canada)	2006 - Assumed Discoveries
Conventional Oil	50	40	10	
Oil Sands	2500		1180	1320
Conventional Natural Gas	530	77	133	320
Shale Gas	1120			1120
Coal	140	90	50	

The natural gas discoveries follow a similar assumption about improvement in technology or increase in prices.

4.4 Energy Production

In energy production, the important parameters to consider are the elasticity parameters from energy production functions and aggregation, and the parameters in the price functions.

In the production functions for heat energy and electric energy, the CES elasticity parameters η and ϑ are set equal to 0.5, which implies an elasticity of substation of 2. The elasticity parameter in aggregation of electricity and heat energy, θ, is also set to 0.5.

The elasticity of substitution between fossil fuels, nuclear and hydro power in the production of electricity captures differences in the ease with which generation can respond to short term fluctuating demand. Intuitively, it seems that a unit of electricity produced from nuclear power is perfectly substitutable with a unit of electricity produced from coal. However, different sources vary in their ability to respond to demand fluctuations, thus it is not clear how substitutable energy sources are in the short run. Currently, we set μ and ϑ equal to 0.5 A similar argument can be made for the elasticity of substitution in heat energy production, and the aggregation of heat energy and electricity.

The share parameter γ in the CES aggregator for heat and electric energy is set to point 0.9.

The elasticity parameter for the fossil fuel price functions, ρ, is set to -0.4. A lower value would make fossil fuel prices more responsive to depletion of the fossil fuel reserves. The parameter value and the functional form for the price functions are from an earlier version of the ANEMI energy sector (see Davies and Simonovic (2009)).

The initial values for the parameters for the alternative energy price function, μ_1 and μ_2, were set equal to 3 and 5 respectively. The parameters decrease linearly over time representing that alternative energy is becoming cheaper over time as technology improves. For the calibration we had a target of 3% alternative heat energy in 2005.

4.5 Investment

The relevant parameters for investment are the aggregate savings rate s, the depreciation rate δ, and the replacement capital weighing factor φ. The aggregate savings rate is set to 0.25, which means that 25% of the generic consumption good produced is used for investment into new capital. The depreciation rate is set to 0.1, which correspond to an annual depreciation rate of 10%.

The weighting factor for replacement capital is triggered when the average total cost of producing electricity from a fossil fuel type is twice the weighted average total cost of electricity. The value of φ is set to 0.5 which means that if the condition is true, then the request for replacement capital is only half of the depreciated capital. The intuition behind this parameter is to improve the adjustment process of the capital stock in electricity production from fossil fuels in response to average cost changes.

4.6 Productivity Parameters

The model productivity parameters are the total factor productivity (TFP) A, and the energy specific productivity terms for electricity and heat energy, A_{El} and A_H. The model also has several assumptions that can be interpreted as implicit increases in productivity.

TFP is assumed to increase at a decreasing rate. TFP growth is 1.6% in 2005, 0.9% in 2050, and 0.6% in 2100. A_{El} and A_H is assumed to grow linearly. The assumption implies that they increase by approximately 1.35% in 2005, 0.9% in 2005, and 0.6% in 2100.

Implicit productivity increases are embedded in the assumptions on fossil fuel discoveries, the price function of alternative heat energy, and the share parameters in the aggregate production function.

Fossil fuel reserves are most commonly defined as the quantity that can be extracted given the current price and available technology. In the assumptions we have made about future discoveries of fossil fuels is an underlying assumption about improvements in extraction technology which comes in addition to our choice of A, A_{El} and A_H.

The parameter paths for the price function for alternative heat energy have similar assumptions embedded in them as they are decreasing over time.

The sum of the share parameters from the aggregate production function, α and β, are assumed to decrease over time. The assumption implies that the share of energy services in final output is decreasing. The assumption here is that technology improvements reduce the energy intensity of the economy as a whole

5 Results

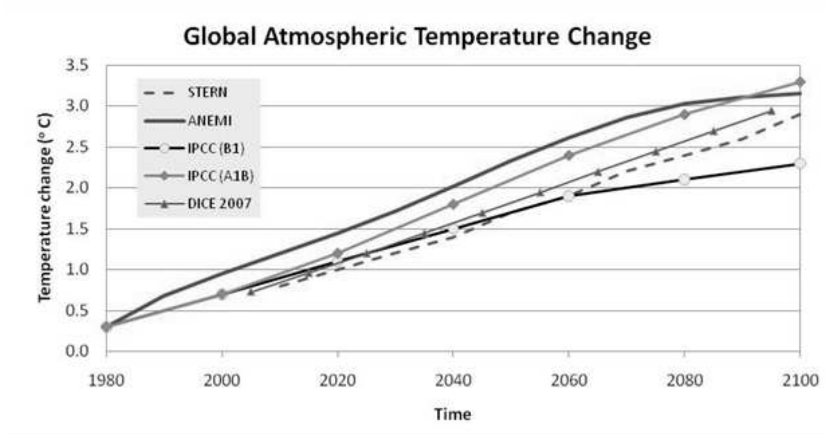
In this section we discuss the results of an illustrative experiment. To highlight how Canada differs from the global average, we compare the results from our Canadian economy to those of the ANEMI model for the same carbon tax policy. A key message of the experiment is while there are significant benefits to the world in moving to mitigate GHG emissions, the direct benefits to Canada are much smaller.

5.1 Global Baseline from ANEMI

Before turning to the Canadian economy, it is worthwhile briefly discussing the global projections that we take from the ANEMI model.

As Figure 6 shows, the baseline temperature projections implied by the ANEMI model are comparable with a number of well known estimates of future temperature change. This suggests that the global path of emissions and temperature changes that we feed into our model are reasonable.

Figure 6: Baseline Temperature Projections from ANEMI



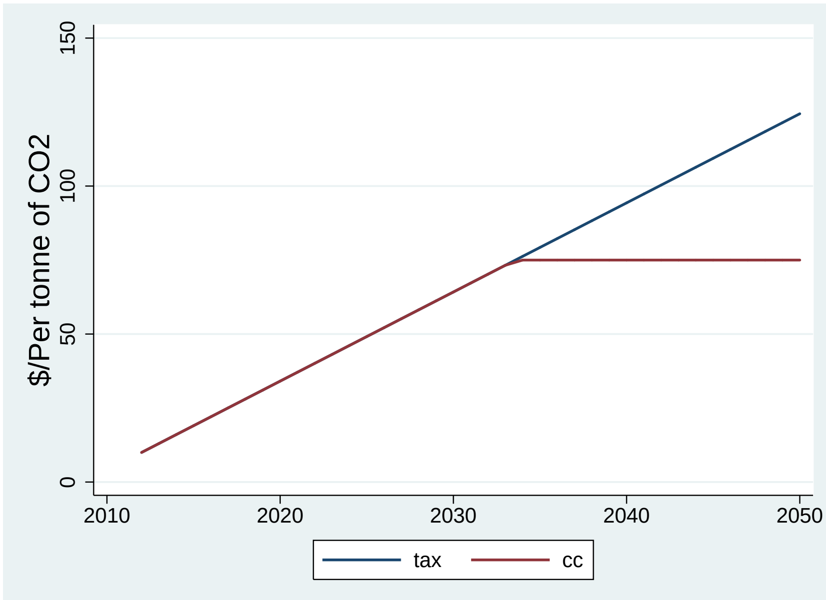
5.2 Carbon Tax Impact on Canada

The thought experiment we focus on is based on the carbon tax required to maintain the level of CO2e below 550 ppm. The path of the tax we consider is computed using two additional restrictions. First, we assume that a carbon capture and storage technology for coal fired electricity is available at a real cost of $75 per tonne CO2e . Second, we assume that the tax is introduced in 2012 and is increased linearly until 2080. The resulting tax is plotted in Figure 7.

Figure 8 shows the difference between GDP per capita for the business as usual case (the baseline run) and the carbon tax experiment for Canada and the world economy. Initially, the carbon tax results in a lower level of GDP, as higher energy prices result in lower energy consumption and thus GDP. In Canada, this effect is not offset by reduced climate damages, since the calibrated damage function for Canada initially features small positive effects. As a result, this carbon tax policy results in a much larger decline in the level of GDP in Canada, with the trough in Canada in 2050 roughly 2.5% below the business as usual case. In contrast, the largest decline in the global economy is at less than 1% in 2020, with the carbon tax economy resulting in higher levels of GDP per capita by 2045 than the business as usual case.

As an alternative way of highlighting the differential impact of this carbon tax policy, we also compute the present value of this policy over 2012-2080 for Canada and the world in trillions of 2005 Canadian dollars. Table 5 highlights

Figure 7: Carbon Tax in Experiment

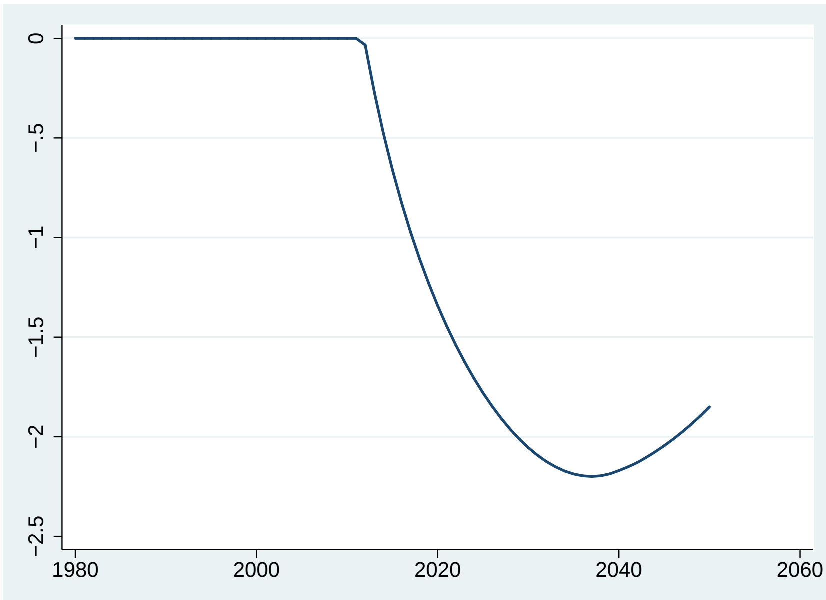


two key messages. First, from a global perspective, a carbon tax that keeps the stock of GHG below the 550 ppm mark yields positive net present value even if one truncates the calculations in 2050 (the end of our simulation). While the magnitude of the gains are decreasing in the discount rate used, even for a relatively high value of 5% the gains remain positive. However, the second message from Table 5 is less positive. From a Canadian perspective, this carbon tax policy actually has a negative net present value. This highlights the potentially different incentives facing Canada versus other countries in adopting policies to mitigate GHG emissions.

Table 5: Cumulative Loss Benefit from Tax, 2012 - 2080 (2005 $ Trill.)

Discount Rate	Canada	The World
1%	-2.5	51.2
3%	-1.3	11.6
5%	-0.8	0.2

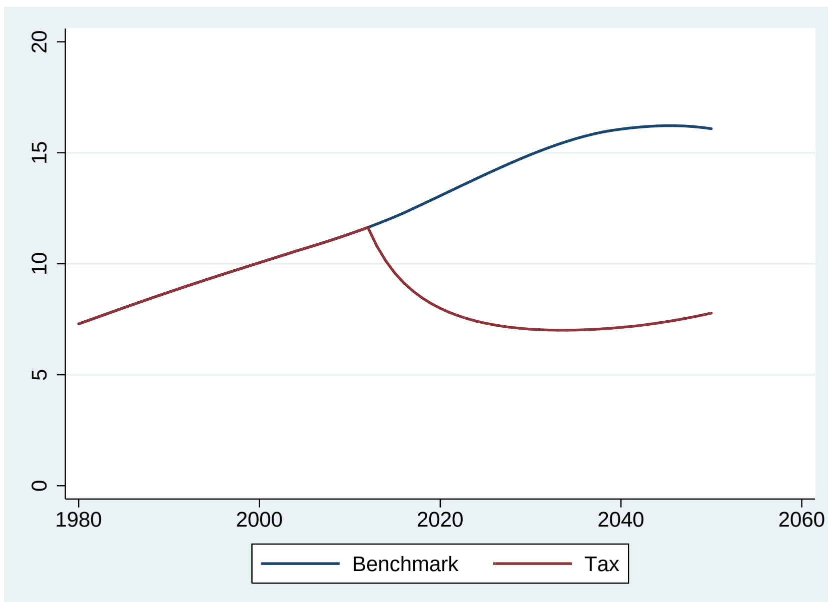
Figure 8: Impact of Carbon Tax on GDP as % of GDP in BAU Case



These differences are driven by two key forces. First, the climate damage functions for Canada and the world are very different. As discussed above, the Canada damage function actually yields small benefits for slight increases in temperature, whereas the global damage function features negative effects that increase relatively quickly with temperature. The second key force is a differential impact of a shift in the price of fossil fuels in Canada versus the world economy. Since Canada is a net exporter of fossil fuels, the initial reduction in fossil fuel prices due to the carbon tax lowers fossil fuel exports and this Canadian GDP. However, over time this effect is partially undone as the reduced level of fossil fuel consumption leads to slightly lower fossil fuel prices over the longer term than the business as usual case.

To better understand these mechanics, it is worthwhile to examine how both total energy use and fossil fuel use respond to the carbon tax in the model. The large decline in total energy used in the production of aggregate energy services in the Canadian economy is visible in Figure 9. For the baseline, the hump shape in total energy input is a result of increasing fossil fuel prices, which are exogenously given, from the global model. Not surprisingly, the path of industrial GHG emissions closely resembles that of total energy, with emissions declining even faster than energy use as the carbon tax induces a shift away from relatively more expensive fossil fuels towards alternative energy sources (see Figure 10). As a result, energy intensity (energy per dollar of GDP) declines significantly in response to the carbon tax (Figure 11).

Figure 9: Total Energy Used in the Production of Aggregate Energy Services in Canada



The results in Figures 9 - 11 focus on the simulation up to 2050. After 2050, fossil fuel prices in the business as usual case begin to increase rapidly as the stock of remaining reserves declines in size. This rapid increase in price leads to a similar effect of a carbon tax, and results in a significant reduction in energy intensity. In contrast, the carbon tax economy features a much smaller secular trend in the price of fossil fuels, as the reduction in fossil fuel consumption induced by the carbon tax slows the depletion of reserves and thus delays the market driven increase in their price. As a result, the level of energy intensity in the business as usual case and the carbon tax tends to converge to a similar level by 2080.

Figure 10: Industrial Emissions in Canada

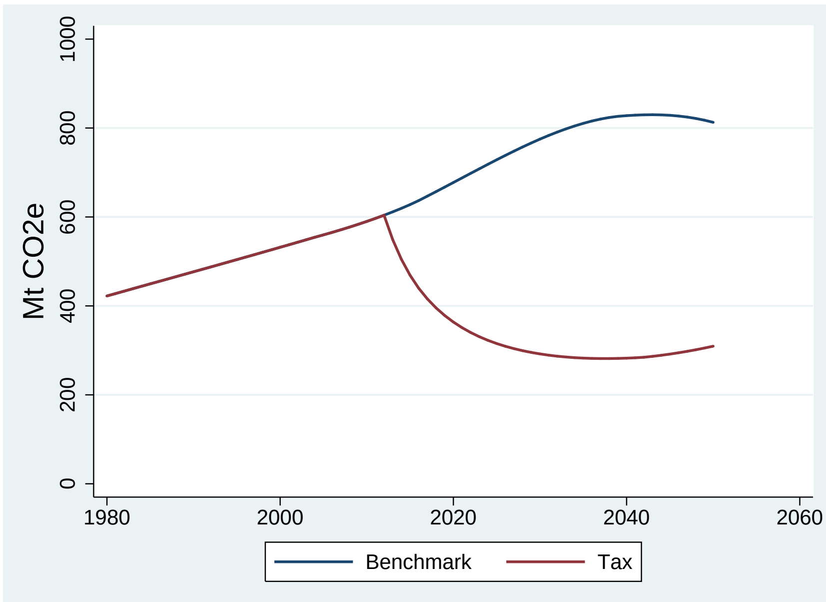
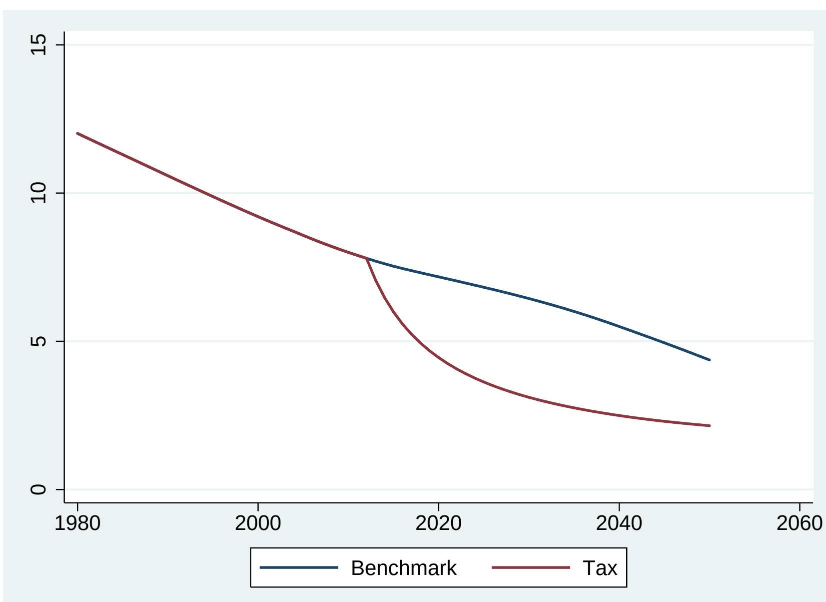


Figure 11: Energy intensity in Canada



6 Conclusion

We examine the relative benefits of policy aimed at mitigating GHG emissions in Canada and globally. We find that while a carbon tax that holds the stock of global emissions below the 550 ppm level would yield positive net benefits for the world economy, the impact of such a tax on the Canadian economy would be negative. This result is largely driven by our finding that the damages from small increases in temperature are much smaller in Canada than in the rest of the world.

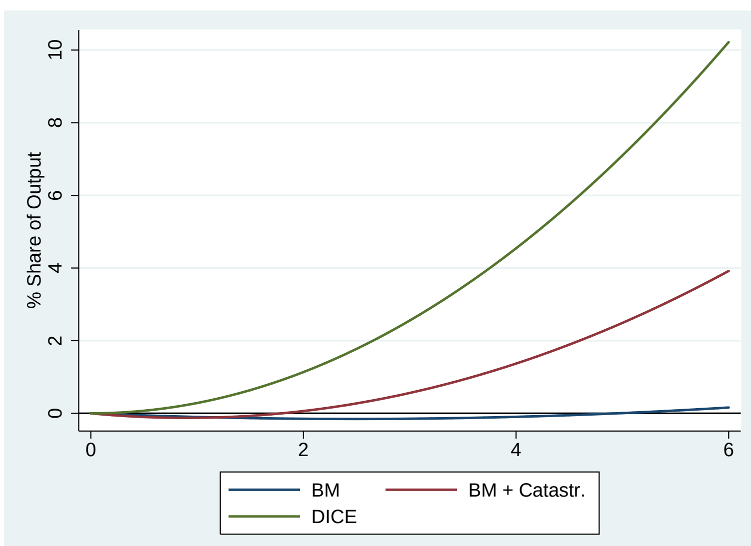
Appendix A: Catastrophic Damages

Nordhaus and Boyer (2000) estimate the catastrophic impact from climate change based on survey responses from experts in the scientific community. Survey respondents were asked about the likelihood of low-probability, ”high consequence” events resulting from climate change. (Here, ”high consequence” means a 25 percent loss in global income indefinitely). They find that:

For the US, the Willingness to Pay (WTP) to avoid catastrophic risk of climate change is 0.45% of GDP at $T = 2.5°$ of warming, and 2.53% at $T = 6°$ of warming. For the world, the WTP to avoid catastrophic risk of climate change is about 1% of GDP at $T = 2.5°$ of warming, and 7% at $T = 6°$ of warming (depending on use of output or population weights).

Using the estimates for the U.S. catastrophic impact I re-estimate our Canadian damage function. In figure 12, the new damage function is displayed together with our old (Benchmark) damage function and the global damage function from Nordhaus (2008).

Figure 12: Adding Catastrophic Damages



Note: x-axis displays increase in degrees Celsius over base year. Economic damages are positive, benefits negative.

Interestingly, Mendelsohn's estimates of market damages seem negligible compared to potential catastrophic damages suggested by Nordhaus and Boyer (2000).

As a comparison, Ackerman et al. (2009) compute annual damages from climate change as a percentage of GDP in 2100. Over 5000 runs of the the PAGE2002 model, based on the IPCC A2 scenario,[10] their results suggest that catastrophic damages in terms of percentage loss of GDP are 4 to 5 times larger for the world compared to the United States. According to these results, the difference between the damage functions in Figure 12 is understated.

Appendix B: Precipitation Sensitivity Analysis

Mendelsohn (2001) reports regional climate damages for five sectors (Agriculture, Forestry, Energy, Coastal Structures, and Water Resources) at varying degrees of warming (1.5, 2.5, and 5.0 degrees Celsius) and varying levels of precipitation (0%, 7%, and 15% over 1990 levels) in 2060.

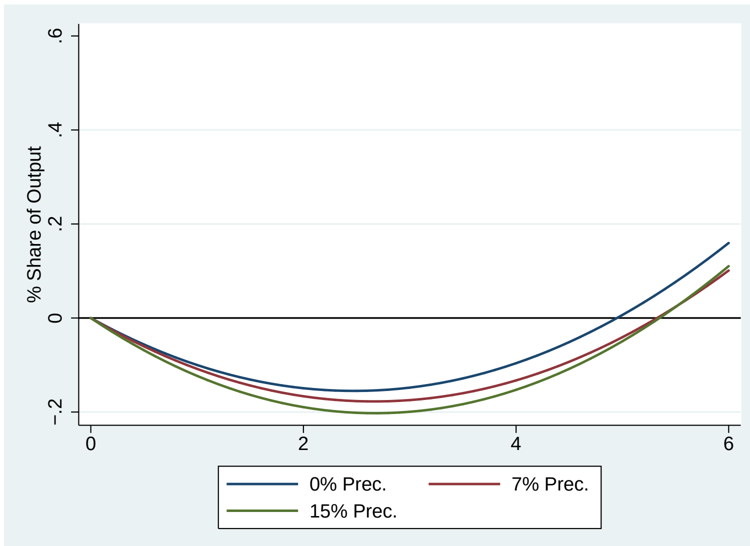
Our damage function was constructed using the damage estimates at 2.5 and 5.0 degrees of warming and 0% increase in precipitation for the four northern U.S. regions. Figure 13 shows the calibrated damage functions for 7% and 15% increase in precipitation from Mendelsohn's scenario analysis. At 7% and 15% increase in precipitation, almost all of the regions experience either higher benefits (or lower damages), and consequently, the damage functions for these scenarios fall below the benchmark calibration. See pages 193 and 203 in Mendelsohn (2001) for details.

Appendix C: NRTEE Forestry Damage Estimates

In a recent report published by the National Roundtable on the Environment and the Economy (NRTEE, 2011), regional damages to the forestry sector are

[10] Projections of GDP, population and emission of green-house gases are taken from the 2001 version of IPCC scenario A2. A2 is the IPCC scenario with the second highest emissions. At the83rd percentile it predicts a global average temperature increase of 5.4 degrees C in 2100. Its mean prediction is 3.4 degrees C in 2100.

Figure 13: Damage Functions for Canada: Precipitation



Note: x-axis displays increase in degrees Celsius over base year. Economic damages are positive, benefits negative.

estimated based on impacts of climate change on fires, forest productivity, and pests such as the pine beetle. Table 6 shows the estimated damages.

The estimates were drawn primarily from research conducted by the Canadian Forest Service at Natural Resources Canada. Damage estimates from forest fires are based on forecasts of forest ares burned in different regions due to climate change. Damage estimates from forest productivity and pests are based on qualitative assessments stemming from judgments based on existing literature.

Overall, damages of $2 - 17 billion for Canada in 2050 are high compared to Mendelsohn's estimated benefits to the forestry sector in the Northern United States.

Table 6: NRTEE Forestry Damages

Region	Low Climate Change Slow Growth		High Climate Change Rapid Growth	
B.C.	-0.5B	0.18%	-3.1B	0.44%
Alberta	-0.2B	0.06%	-1.0B	0.14%
Prairies	-0.5B	0.33%	-3.3B	0.85%
Ontario	-1.0B	0.11%	-7.4B	0.31%
Quebec	-0.3B	0.08%	-2.1B	0.23%
Atlantic	-0.1B	0.07%	-0.5B	0.21%
Canada	-2.4B	0.12%	-17.4B	0.33%

Notes: $ 2008
Source: Table 4, Paying the Price, page 53, (NRTEE, 2011).

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