Future of Canadian Air Quality and Related Health Benefits from Climate Change Mitigation

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Air pollution has been recognized as the world's largest environmental health risk. Climate change is expected to exacerbate air pollution. Mitigating the "climate penalty" of climate change on air quality yields air quality-related "co-benefits" by protecting human health. This study quantifies Canada's air quality-related co-benefits from reducing greenhouse gases under different policy scenarios. It achieves this by adapting the MIT-IGSM-CAM-Chem-BenMAP framework for use in Canada. This integrated framework was used to analyze the all-cause premature mortality and economic impacts due to changes in fine particulate matter ($PM_{2.5}$) and ground-level ozone pollution in Canada under climate change and climate policy at mid- and end-of-century in comparison to the beginning of century.

Modelled air quality concentrations were validated with Canada's National Air Pollution Surveillance program station data, resulting in acceptable relative errors of 66% and 47% for ground-level ozone and $PM_{2.5}$, respectively. Without climate policy, ozone concentrations in Canada will generally decrease, with the exception of the Greater Toronto Area, while the $PM_{2.5}$ concentrations will increase over the century. The impact of the increase in $PM_{2.5}$ greatly outweighs the impact of the decrease in ozone, leading to an overall increase in excess annual premature mortality between 1,300 (95% confidence interval: 880, 1,700) and 3,000 (1,500, 4,500) for mid-century, and between 2,800 (1,900, 3,700) and 6,500 (3,300, 9,700) in 2100, under the reference scenario. This corresponds to economic damages between 16 (1.5, 44) billion and 21 (2.0, 5.8) billion dollars (2021 CAD) for mid-century, and between 45 (4.3, 120) billion and 90 (8.5, 250) billion dollars for end-of-century. Climate policies consistent with the Paris Agreement are expected to increase mean ozone concentrations slightly while greatly decreasing mean $PM_{2.5}$ concentrations in key urban areas including Toronto, Montreal, Calgary, and Vancouver. This leads to a net decrease in annual premature mortality between 590 (370, 810) and 1,500 (690, 2,200) for mid-century, and between 1,800 (1,200, 2,300) and 4,800 (2,200, 7,000) for end-of-century, using the American Cancer Society Study and the Harvard Six Cities Study as the $PM_{2.5}$ health impact function, respectively. Using the American Cancer Society Study as the $PM_{2.5}$ health impact

function, this yields annual air quality co-benefits between 8.3 (0.78, 22) billion and 11 (1.0, 29) billion dollars for 2050, and between 32 (3.0, 87) billion and 66 (6.2, 180) billion dollars by 2100. The yields increase using the Harvard Six Cities Study as the $PM_{2.5}$ health impact function, ranging between 21 (1.8, 59) billion and 28 (2.5, 80) billion dollars for 2050, and between 79 (7.0, 220) billion and 160 (14, 460) billion dollars by 2100. This represents a near doubling of the current annual air quality burden in Canada, estimated at $50 billion. These co-benefits do not represent the main goal of climate policy, and but they still serve to slightly offset compliance costs. When compared to the cost of implementing the policies, the benefits have the potential to offset between 1% and 6% of annual GDP loss. This is lower than the potential for 5% to 17% cost offset in the case of the United States, as the policy cost for Canada is a higher fraction of its GDP due to its emission intensive economy.

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First and foremost, I would like to thank Dr. Rebecca Saari for guiding me through it all. She has been an amazing teacher, leader, and mentor in these very important stages in my life, from my senior undergraduate year to the entirety of my graduate studies.

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List of Abbreviations

Term	Description
BenMAP-CE	Benefits Mapping and Analysis Program – Community Edition
CAC	Criteria Air Contaminants
CAM-Chem	Community Atmosphere Model with Chemistry
CD	Census Division
CDUID	Census Division Unique Identifier
CO_2	Carbon Dioxide
ECCC	Environment and Climate Change Canada
EPA	United States Environmental Protection Agency
GHG	Greenhouse Gas(es)
IAM	Integrated Assessment Model
IMPROVE	Interagency Monitoring of Protected Visual Environments
INDC	Individually Determined National Contribution
IPCC	Intergovernmental Panel on Climate Change
MESM	MIT Earth System Model
NAAQS	National Ambient Air Quality Standards
NAPS	National Air Pollution Surveillance
NCAR	National Center for Atmospheric Research
NOx	Nitrogen Oxides (NO + NO_2)
P37	Policy Aligning with Radiative Forcing 3.7 W/m^2
P45	Policy Aligning with Radiative Forcing 4.5 W/m^2
$PM_{2.5}$	Particulate Matter (with Aerodynamic Diameter Less than 2.5 µm)
POET	Precursors of Ozone and their Effects in the Troposphere
ppb	Parts Per Billion – Volume
ppm	Parts Per Million – Volume
REF	Reference Scenario

UNFCCC	United Nations Framework Convention on Climate Change
VSL	Value of a Statistical Life
VOC	Volatile Organic Compounds
WGS	World Geodetic System

1. Introduction

1.1 Problem of Air Pollution under Climate Change

Air pollution has been recognized as the world's largest environmental health risk (Forouzanfar et al. 2016; Garcia-Menendez et al. 2015). Despite being a large energy producer, Canadians are fortunate to have some of the best air quality in the world, due to factors such as low population density, a mostly combustion-free energy grid, and relatively low anthropogenic emissions (Aliakbari and Stedman 2018). Nevertheless, Canada's air pollution burden continues to cost Canadians. It was estimated to include about 7,100 $PM_{2.5}$-related premature deaths and $53 billion (CAD 2018) in 2015 (Howard, Rose, and Rivers 2018). Most deaths associated with air pollution occur in other parts of the world like Asia, Africa, and Europe, where air quality is a growing major health concern.

Climate change is another area of growing attention, as the effects of climate change are felt around the world. There are global mitigation efforts to reduce the amount of greenhouse gases (GHG) from industrial sectors that are considered major contributors. These sectors include energy, transportation, and industrial activities. These sources of GHG are also major sources of air pollutants. Hence, policies to reduce GHG emissions will also reduce emissions of air pollutants from the same sources. This means that climate policy can reduce air pollution, and its attendant health risks and economic damages. There are thus health-related *co-benefits* to reducing GHG in the world. These co-benefits arise through what is termed the "co-emitted pollutants" pathway, as shown in Figure 1.

There are further interdependencies between climate change and air quality, as depicted in Figure 1. Air pollution depends not only on emissions, but on weather. Since climate is the average weather, climate change will affect air pollution. This effect of climate change on air pollution is termed the "climate penalty". Climate policy can then also yield air quality co-benefits by reducing this climate penalty. This is shown as the “climate penalty pathway” in Figure 1.

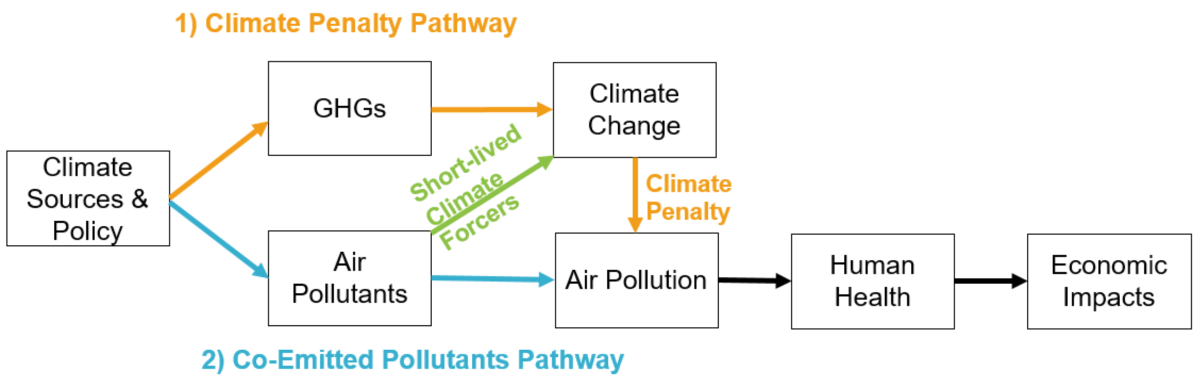


Figure 1. Air Quality Impacts of Climate Change and Climate Policy (adapted from figure by J. Jason West). The Climate Penalty Pathway refers to the change in greenhouse gases through policy or climate sources, which impacts climate change, hence reducing or increasing air pollution through climate penalty. Increasing climate change is expected to increase air pollution.

Air pollutants are also expected to impact climate change as short-lived climate forcers. For example, particulate matter can increase or decrease warming while ground-level ozone is a greenhouse gas (Fiore, Naik, and Leibensperger 2015). Meanwhile, the climate penalty is generally expected to make air pollution worse. However, climate change can alter regional meteorology in positive or negative ways. For example, climate change can affect vertical mixing in the air (known as “ventilation”), either decreasing it and trapping pollution near the surface, or enhancing it and decreasing pollution (Fiore, Naik, and Leibensperger 2015).

Many studies have shown the significance of air quality co-benefits of climate policy. Most studies focus on the “co-emitted pollutants pathway”, finding that they can completely offset the cost of efficient climate policy (Thompson et al. 2014; Saari et al. 2015). Few studies examine the effect of the climate penalty, which is important for understanding the cost of inaction on climate change. Canada’s climate plan aims for net-zero emissions by 2050 which will have related health co-benefits (Government of Canada 2020). The United States has studies that quantify the climate-penalty co-benefits of reducing greenhouse gases, but

Canada currently lacks this information (Saari et al. 2019). Recent global or U.S. studies provide a basis to expect thousands of annual deaths associated with the climate penalty by 2100 in Canada, but no studies have yet quantified the implications for Canadians (Saari et al. 2019; Silva et al. 2017).

1.2 Research Questions

To address this gap, this study aims to answer two research questions:

1. **Climate Penalty (Reference Case):** What is the effect of climate change on premature mortality associated with ozone and fine particulate matter in Canada in 2050 and 2100?
2. **Climate Policy (Two Policy Cases):** What are the co-benefits of reducing the climate penalty through climate change mitigation in Canada under different levels of policy at mid-century and end-of-century?

1.3 Thesis Structure

Following the introduction to the study, the background and literature are reviewed to provide context to the problem, discussing climate change, air pollutants, the Paris Agreement, tools for evaluating the climate penalty and co-benefits, and prior studies there-of. Data and methodology are described next, starting with the overview of the methodological approach, sourcing the necessary data for the study, as well as describing the steps taken to validate and apply a Canadian modelling framework. Next, the results of the study are discussed, addressing the answers to the above-mentioned research questions related to the climate penalty and climate policy impacts. This is finally followed by the conclusions of the study, work cited, and supporting appendices.

2. Background and Literature

2.1 Air Pollution

Air pollution is the introduction or presence of substances in the atmosphere which can potentially be harmful, usually to humans or the environment. This differs from greenhouse gases that are not directly harmful when inhaled, but which can have a negative indirect influence on humans and the environment. The word “contaminant” is sometimes used as a synonym for “pollutant” in regulatory contexts. The Government of Canada has identified seven Criteria Air Contaminants (CAC): sulphur oxides (SO_2), nitrogen oxides (NO_x, the family of NO and NO_2), volatile organic compounds (VOC), particulate matter (PM), carbon monoxide (CO), ammonia (NH_3), and ground-level ozone (O_3) (Government of Canada 2017). Of these pollutants, ground-level ozone and particulate matter are responsible for the most widespread violations of the U.S. National Ambient Air Quality Standards (NAAQS) (Fiore, Naik, and Leibensperger 2015). Three of these pollutants are considered to increase the risk of premature death and are included in Canada’s Air Quality Health Index: ozone, particulate matter, and nitrogen oxides (as NO_2) (Environment and Climate Change Canada 2019a).

Of these three pollutants, the vast majority of mortality impacts are due to exposure to particulate matter. While NO_2 is considered to have separate mortality impacts in Canada, it is not included in global disease burden assessments (Howard, Rose, and Rivers 2018). Considering its relatively small impact, and data availability issues discussed later, NO_2 is excluded from this study.

The anthropogenic sources for these air pollutants in Canada include common activities and sectors such as transportation, construction, heating, manufacturing, oil-and-gas, and power generation. Many transportation vehicles – such as airplanes, ships, and cars – are powered by the combustion of fossil fuels which contribute to atmospheric concentrations of $PM_{2.5}$ and O_3. The oil-and-gas industry is also a significant emitter of pollutants in its processes, which include drilling, refining, and transportation. The power generation sector releases pollutants into the atmosphere similar to the transportation sector when the generation involves the combustion of fossil fuels such as coal, natural gas, and diesel. Air pollution is becoming a significant global problem as many major metropolitan hubs are becoming over-populated resulting in high emissions from transportation, construction, and air conditioning.

2.1.1 Fine Particulate Matter

Fine particulate matter ($PM_{2.5}$) is defined by its size as it cannot be removed by the human body's biological filtration processes in the human respiratory system. The subscript, *2.5*, that follows *PM* indicates that its aerodynamic diameter is less than or equal to 2.5 microns. As it is described by its diameter, there is no specific chemical formula for particulate matter. $PM_{2.5}$ can be *primary* (emitted directly) or *secondary* (formed in the atmosphere from precursor gases or particles). Globally, the majority of $PM_{2.5}$ in the air is primary $PM_{2.5}$ released from natural sources like soil dust, sea salt, and forest fires (Hinds 1998). Globally, anthropogenic sources contribute less than 15% of $PM_{2.5}$ in the atmosphere. Of the anthropogenic contribution, the majority of $PM_{2.5}$ is secondary, meaning that it is formed from the release of precursors, largely from combustion and chemical processes.

In Canada, wildfires are the largest source of $PM_{2.5}$ in the air, followed by transportation, residential combustion, and industry (Meng et al. 2019) (see Figure 2). This includes a mixture of natural and anthropogenic sources, as well as primary and secondary formation.

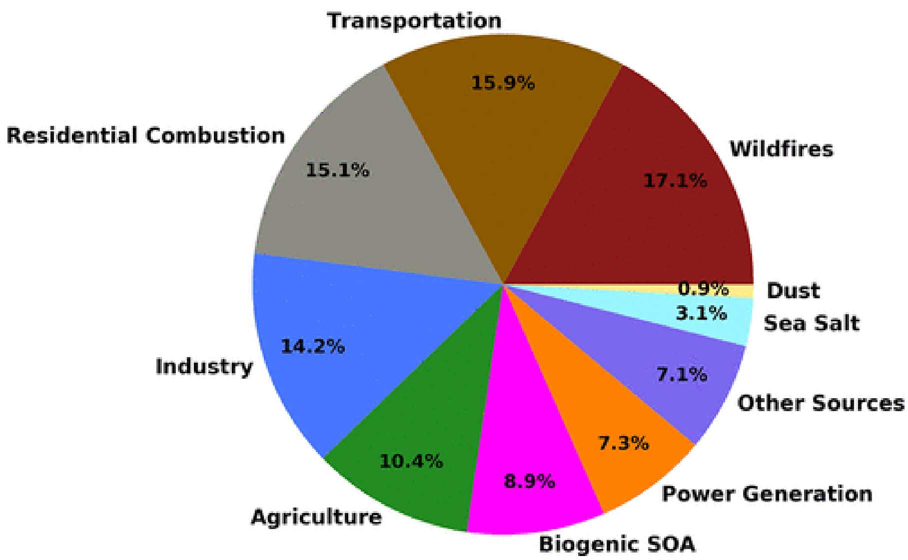


Figure 2. Sectoral Contribution of Emissions to Fine Particulate Matter ($PM_{2.5}$) in Canada (from Meng et al. (2019)). SOA stands for secondary organic aerosol.

Of all sources of $PM_{2.5}$, those over which policy-makers have the most control are anthropogenic, primary emissions. In Canada, the majority of primary anthropogenic $PM_{2.5}$ emissions originate from construction and roads, accounting for a total of 59% (Environment and Climate Change Canada 2020a). This is followed by crop production, and home firewood burning, accounting for 24% and 10%, respectively (see Figure 3).

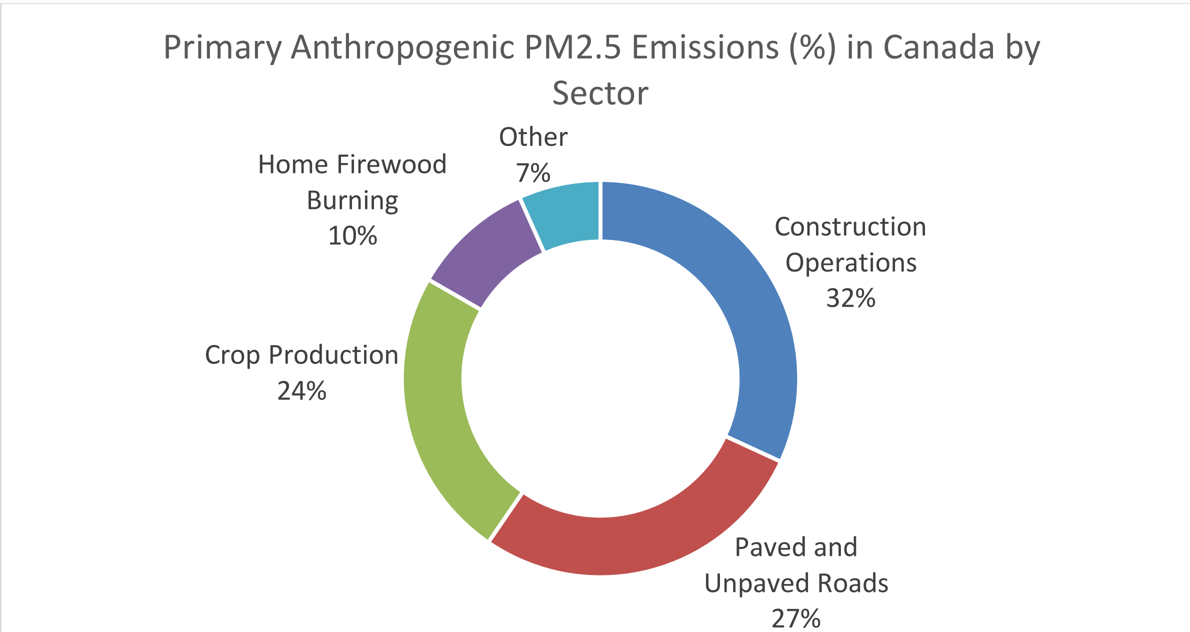


Figure 3. Anthropogenic Primary $PM_{2.5}$ Emissions in Canada By Sector (Environment and Climate Change Canada 2020a). Construction Operations and Roads account for the majority of $PM_{2.5}$ emission sources, followed by Crop Production and Home Firewood Burning.

Nationally, the emissions of $PM_{2.5}$ have been between 1.3 and 1.8 gigatonnes per year for the last two decades (Environment and Climate Change Canada 2020a). However, urban areas with increasing population density suffer from higher particulate matter exposure and affect more people. Nearly one-third of Canadians live within 250 metres of a major road and thus are exposed to traffic emissions, with the highest percentages living in Ontario and British Columbia (SOCAAR 2019). $PM_{2.5}$ pollution in urban areas is primarily affected by traffic in cities, diesel trucks, brake and tire wear. Another study of 250 urban areas in the world found that only 8% of cities had population-weighted mean concentrations below the World Health Organization guideline for annual average fine particulate matter concentrations (10 $\mu g/m^3$).

The study included three Canadian cities (Calgary, Toronto, Montreal) of which two cities (Toronto and Montreal) were at or above the WHO guideline (Anenberg et al. 2019). This work will study the future concentrations of these pollutants under the effects of climate change.

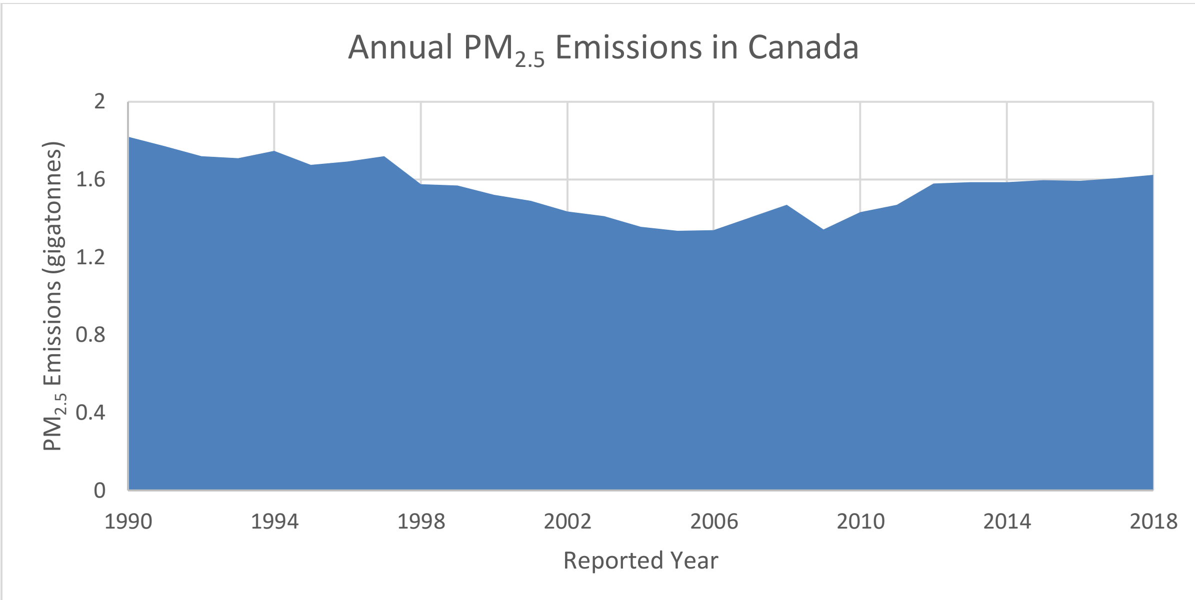


Figure 4. Annual Emissions of $PM_{2.5}$ in Canada from 1990 to 2018 (Environment and Climate Change Canada 2020a).

Long-term exposure to $PM_{2.5}$ can lead to severe health impacts through entering and accumulating in the body through digestion or inhalation. These negative impacts range from increased risk of diseases such as cardiopulmonary diseases, ischemic heart diseases, and lung cancer, including premature death from these diseases (Burnett et al. 2018; Krewski et al. 2009; Lepeule et al. 2012).

2.1.2 Ground-Level Ozone

Ground-level ozone is a secondary pollutant, meaning that it is formed in the atmosphere and not directly emitted from a source. The formation of ground-level ozone can be approximated with two key primary pollutants: volatile organic compounds (VOC) and nitrous oxides (NOx). These pollutants are emitted into the atmosphere, then chemically react in the presence of sunlight to form ground-level ozone.

$$NO_x + VOC + Heat \,\&\, Sunlight = O_3 \; (+ \, other \; products)$$

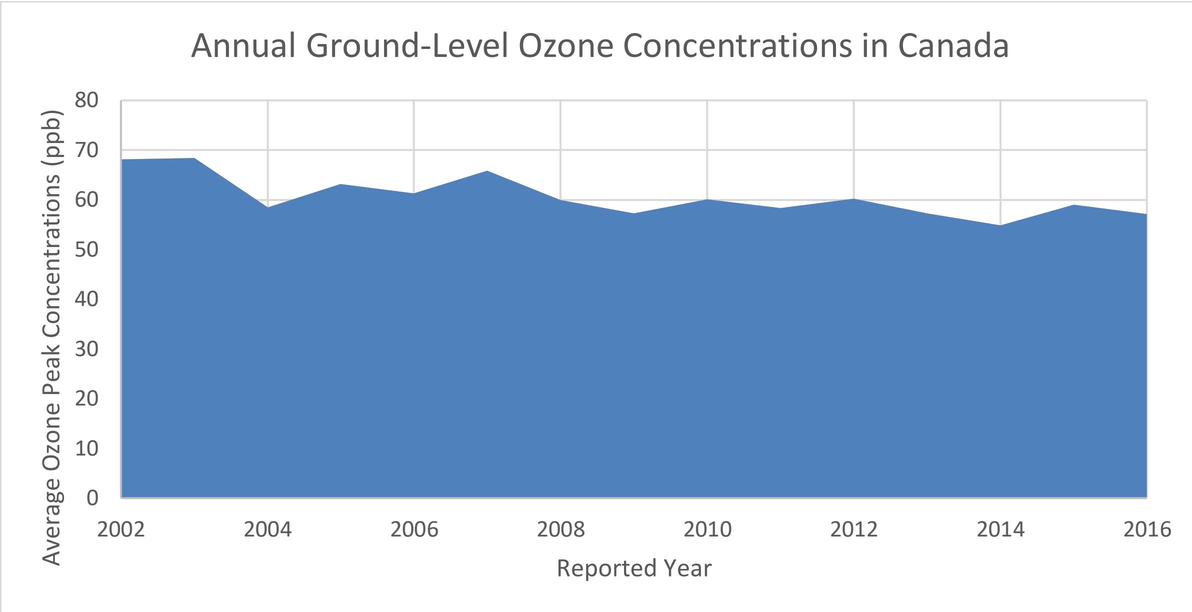
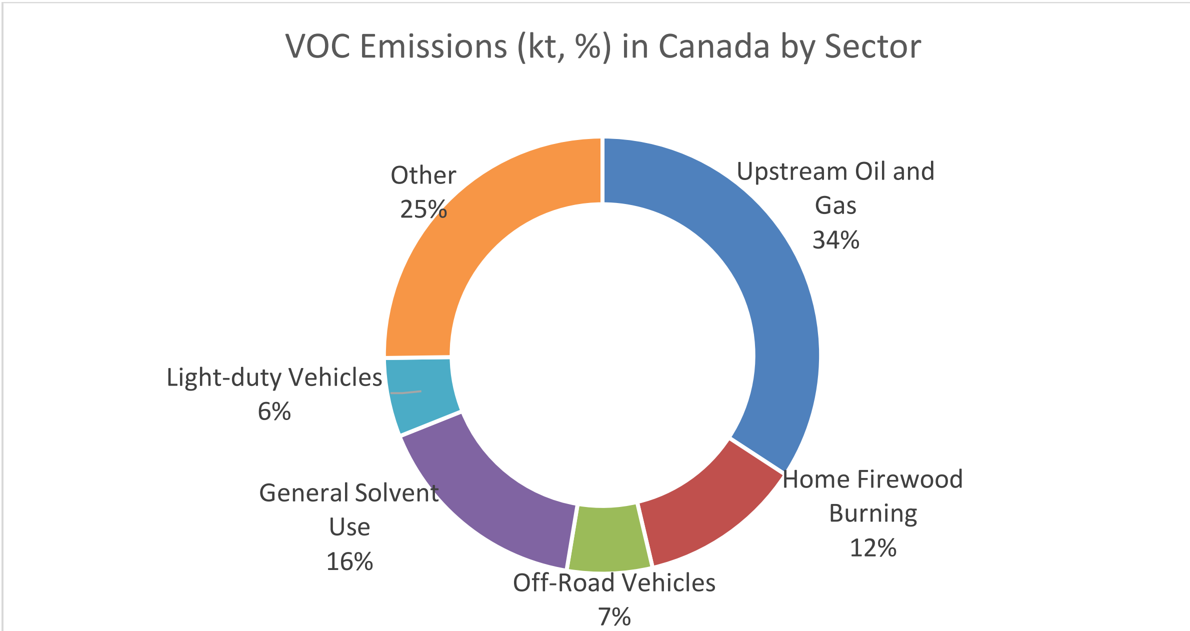


Figure 5. Yearly Average of Peak Ground-Level Ozone Concentrations in Canadian Urban Areas (2002-2016) (Environment and Climate Change Canada 2016).

Annual mean ground-level ozone concentrations across Canada have been fluctuating between 70 ppb and 55 ppb since 2002 (Environment and Climate Change Canada 2016). However, urban areas suffer from higher exposure due to increasing population density and a growing transportation sector with emission-intensive vehicle types such as trucks and SUVs (SOCAAR 2019). Gasoline trucks and vehicles account for 6% of total national VOC emissions while heavy-duty diesel vehicles account for 14% of all NO_x emissions, both contributing to increase of ground-level ozone in urban areas.



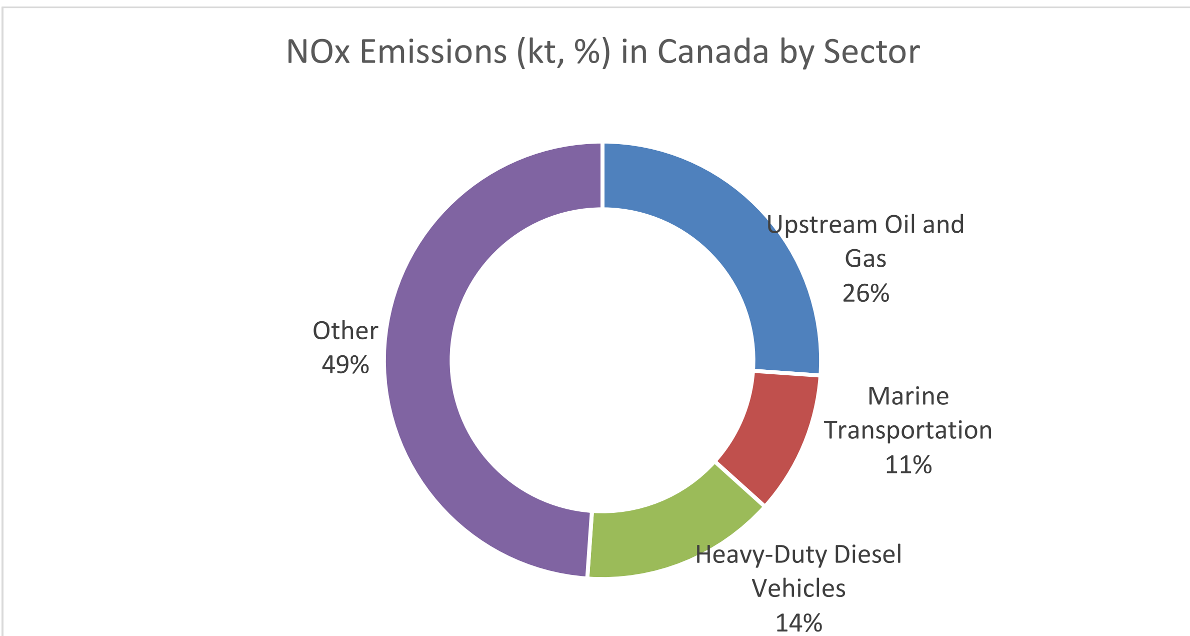


Figure 6. Anthropogenic VOC and NO_x Emissions in Canada By Sector (Environment and Climate Change Canada 2020a). The Upstream Oil-and-Gas industry is the biggest emitters of primary pollutants for ground-level ozone: 34% of VOC emissions and 26% of NO_x emissions. Gasoline and diesel light-duty and heavy-duty vehicles are also notable contributors for both at 13% of VOC and 14% of NO_x emissions.

2.1.3 Transboundary Pollution

Canada's air pollution is not only impacted by emissions within the country, but also globally. As much of the Canadian population lives close to the border shared with the United States, the pollution from across the border must be considered as well (Brook et al. 2013). Freight trucking, for example, has significant cross-border air quality impacts (Mukherjee et al. 2020; Wang et al. 2020). The effect of transboundary pollution requires that models of air pollution in Canada either cover the entire globe or obtain estimates of transboundary pollution from global models. In this study, a global model is used so that transboundary pollution is taken into account in the output. This will be further discussed in Chapter 3.

2.2 Climate Change

Climate change – the long-term change in the global and regional climatic patterns – is a global developing crisis. It includes large climatic changes such as longer dry seasons, heavier precipitation, and more frequent natural disasters (Stocker et al. 2013).

When discussing on the topic of climate change, global warming is often discussed in parallel. Global warming refers to the increase in the global average temperature above preindustrial levels. "Preindustrial" is the benchmark for a climate without significant anthropogenic influence because the Industrial Revolution was the beginning of an extended, ongoing period that has drastically increased the amount of atmospheric greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). Often, climate change mitigation measures involve reducing the amount of these greenhouse gases, usually measured in CO_2-equivalents or CO_2e. This metric uses the global warming potential of carbon dioxide as a reference to describe the global warming potential of other greenhouse gases which would be equivalent to a certain amount of CO_2, hence CO_2-equivalents.

Climate change and air quality are interdependent. First, there are overlapping sources for pollutants and greenhouse gases, such as the transportation and construction sectors. The pollutants studied here are also climate forcers that can influence the global warming rate. Also, climate change may alter air quality through mechanisms including reaction rates, atmospheric ventilation, pollutant deposition, and natural emissions (Isaksen et al. 2009). Hence, as previously discussed and depicted in Figure 1, there are air quality-related co-benefits to reducing greenhouse gases ("co-emissions" co-benefits). Further, there is a climate penalty on air quality, exacerbating the public health burden of air pollution and weakening the effectiveness of abatement measures (Garcia-Menendez et al. 2015).

2.2.1 Climate Change in Canada

The majority of Canada's greenhouse gas (GHG) emissions originate from two sectors: oil-and-gas and transportation, accounting for 26% and 25% of the total, respectively (Government of Canada 2020). While the oil-and-gas industry is the highest emitter of greenhouse gases, it is also an important strategic contributor to Canada's economy. The third most emitting sector is the buildings, or construction, sector at 13% of the total. It is notable that Canada's electricity sector only accounts for 8.8% of GHG emissions. Power is a major source of emissions in many other countries, including in the United States. Canada's grid is expected to be 90% fossil-fuel free by 2030 (Government of Canada 2020).

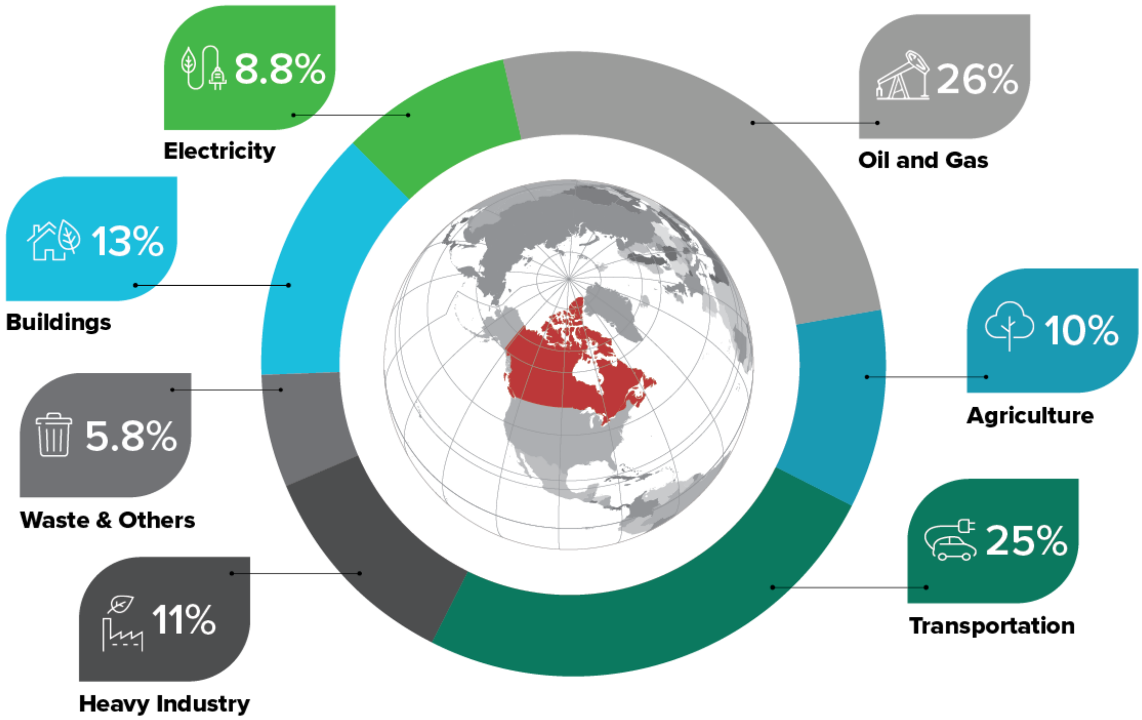


Figure 7. Canadian Greenhouse Gas Sources by Sector (2018). Oil-and-Gas sector and transportation sectors account for majority of greenhouse gas sources.

2.3 Paris Agreement

The global response to the climate crisis involved the formation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 (United Nations Climate Change, n.d.). Decades of negotiations culminated in a truly global agreement adopted by 196 Parties (representing 189 countries) called the Paris Agreement, in December of 2015 (United Nations Climate Change, n.d.). The Paris Agreement is a legally binding international treaty on climate change. Countries in this agreement share a goal to limit global warming to well below 2°C, preferably to 1.5°C, above preindustrial levels by reducing greenhouse gas emissions (Dimitrov 2016). These global goals are to be met through Parties' Individually Determined National Contributions (INDCs) – national commitments to reduce emissions.

Canada's commitment to the Paris Agreement was to emit 513 Mt/yr of CO_2eq by 2030 (reflecting a 30% reduction below year 2005 emissions) (Environment and Climate Change

Canada 2019b). Canada's domestic regulatory actions to reduce emissions include the carbon pricing federal backstop, putting a cost to greenhouse gas emissions – starting from $20 per tonne in 2019 and rising to $50 per tonne in 2022 (Environment and Climate Change Canada 2020b). Recently, Prime Minister Trudeau stated that the carbon tax is gradually continuing to rise to $170 per tonne by 2030, to invest back into climate initiatives in the form of rebates, funding, and improvements to the country's electric vehicle charging infrastructure (Tasker 2020).

This study examines two future scenarios that conform to global attainment of the 2°C and 1.5°C degree goals, respectively. Carbon pricing scenarios aligning with these goals, along with their emissions reductions and costs, will be discussed later.

2.4 Integrated Assessment Modelling of Climate Policy

One critical tool for assessing the effect of climate change and climate policy is the Integrated Assessment Model (IAM) (Schneider and Lane 2005). IAMs are models or modelling frameworks that combine expertise from multiple disciplines. The creation and application of IAMs to global climate change has grown rapidly since 1990 (Parson, Fisher-Vanden, and Karen 1997). IAMs representing earth and human systems are now ingrained in the processes of the Intergovernmental Panel on Climate Change (IPCC), the scientific assessment body developed to support the UNFCCC (UNFCCC 2021). IAMs are particularly useful for estimating the costs of conforming to climate policy needed to reach different emissions targets. While they also estimate economic damages associated with climate change, this is often based on simplified damage functions (Greenstone, Kopits, and Wolverton 2013) considered ad-hoc by some economists (Pindyck 2013).

Consequently, some IAM groups take a different approach. Instead of estimating all climate-related impacts in a damage function, they couple these models to physical damage models appropriate for each specific impact. The Massachusetts Institute of Technology (MIT) Joint Program on the Science and Policy of Global Change, which developed the MIT Integrated Global System Modelling Framework (IGSM), is one such group (Monier et al. 2018). The MIT IGSM is used to estimate specific impacts of climate change and climate policy. One such impact is the climate penalty, i.e., the effect of climate change on air pollution, and its associated economic impacts. Most of these impacts are due to the effect of air pollution on human health. Estimating these impacts thus requires the use of health impact assessment.

2.5 Health Impact Assessment

This study involves the assessment of health impacts due to changes in air quality, specifically, due to changes in outdoor, ground-level concentrations of fine particulate matter and ozone. The general steps involved in health impact assessment are enumerated below. In parentheses, the source of data used in this study is mentioned, which is discussed in detail in Chapter 3.

1. Estimate change in ambient air quality (CAM-Chem model data)
2. Determine change in population exposure (Canada Census data)
3. Estimate change in incidence and valuation of health impacts (BenMAP using health impact functions and VSL that relate pollution to health)
4. Characterize results (visualizations, tables, report, etc.)

2.5.1 Health Impact Functions

Health impact functions relate outdoor exposure to air pollution to resulting increased health risks. They are designed to estimate how many additional cases of death or disease will arise in a given population due to an increase in exposure to air pollution. They provide statistical, population-level estimates based on increase in risk, and do not predict individual cases in individual people.

To estimate the number of additional cases of death or disease due to air pollution exposure, the health impact function (also called a concentration-response function) is applied to the population of interest and relevant baseline health conditions. In epidemiology, the extra health risk due to pollution is termed “excess risk”, and the additional resulting cases are “attributable excess incidences”. A typical equation for estimating excess incidences of health outcomes due to air pollution exposure follows:

$$\Delta Mortality = Y_0 \times Population \times (1 - \exp(-\beta \Delta x))$$

Where:

Y_0 is the baseline incidence rate, in units of incidences per persons, usually 1,000

β is the risk coefficient for the health endpoint of interest, and

Δx is the change in pollutant concentration between two scenarios.

The above equation shows a log-linear form for the concentration-response function. This log-linear form is commonly used in BenMAP, and in U.S. regulatory impact assessment. However, simpler linear forms and more complex forms that vary throughout the dose-response curve are also used in the literature (Burnett et al. 2018).

2.5.2 Economic Valuation

Increased risk of death and disease results in economic losses. Some of these losses appear directly in the economy (so called "market effects"), such as lost wages, lost worker productivity, and health care costs (Saari, Thompson, and Selin 2017). Other losses are meaningful to people, but do not appear directly in the economy ("non-market effects"), such as pain and suffering. "Willingness to pay" to avoid an increase in health risk is an economic concept that is meant to capture the full economic loss associated with that increased risk, including market effects and non-market impacts like pain and suffering.

Estimates of the willingness-to-pay to avoid increased health risks can be used to calculate the economic losses associated with increased air pollution. Many studies have estimated these risks (Viscusi, Harrington, Jr., and Sappington 2018). These studies find that, of all health outcomes associated with air pollution, the value of avoided mortality risk dominates. When the health-related economic impacts of air pollution are quantified, premature mortality is found to contribute over 90% of the economic impact (Saari et al. 2015).

The economic value of reduced mortality risk is quantified using the Value of a Statistical Life (VSL). VSL is defined by the EPA as "the monetary value that a group of people are willing to pay to slightly reduce the risk of premature death in the population" (U.S. Environmental Protection Agency 2017). Thus, the VSL is a statistical, population-based measure related to small changes in risk, and is *not* the value of a life, nor the value someone would pay to avoid certain death (Cameron 2010). The VSL relates the mean willingness to pay with avoided risk according to the following equation:

$$VSL = \frac{Mean\ Willingness\ To\ Pay}{Avoided\ Risk}$$

BenMAP includes several distributions representing the VSL and associated uncertainty. This study uses the version most grounded in the literature, based on 26 VSL studies, with a mean value of $8,705,114 in 2015 USD.

2.6 Health Burden Due to the Climate Penalty

Ozone and $PM_{2.5}$ are both secondary pollutants that form in the air. This means their formation is affected by the weather, and thus the climate. As previously described, the effect of climate change on air pollution is termed the climate penalty (Wu et al. 2008). While these effects are complex and uncertain, numerous studies have reviewed them (Fu and Tian 2019). One study by Fiore, Naik, and Leibensperger (2015) depicts these complex relationships in a figure reproduced here as Figure 8.

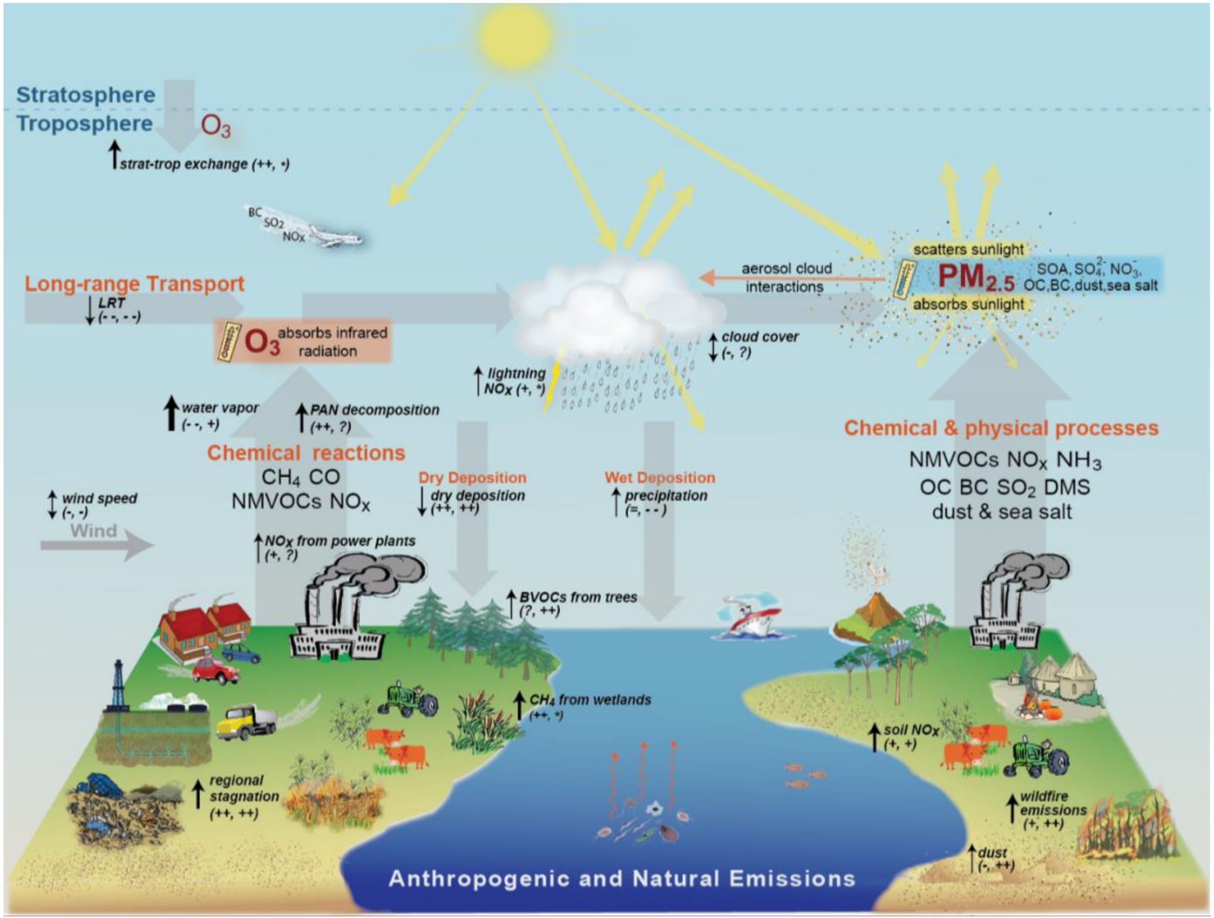


Figure 8. Air Quality and Climate Connections (Fiore, Naik, and Leibensperger 2015). Orange text shows atmospheric processes. Black arrows show sensitivity of processes to warming (increase is up; decrease is down; double-headed arrow is unknown). In parentheses is how O_3 and $PM_{2.5}$ respond, respectively (For double-headed arrows, the O_3 and $PM_{2.5}$ response denoted is for an increase in the process): ++ consistently positive, + generally positive, = weak or variable; - generally negative, -- consistently negative, ? uncertainty in the sign of the response, and * the response depends on changing oxidant levels.

Figure 8 shows that climate change can either increase or decrease concentrations of ozone and $PM_{2.5}$. For example, climate change can increase atmospheric water vapour (as shown by the black upwards arrow in the figure). This will have consistently decreasing effect on ozone (--) but lead to an increase in $PM_{2.5}$ (+). In Canada, the overall effect of climate change on air pollution is expected to result in a decrease in ozone, and an increase in PM2.5 (Kelly, Makar, and Plummer 2012).

Overall, the climate penalty is expected to increase health risks by increasing air pollution, as described in recent reviews (Sujaritpong et al. 2014; Madaniyazi et al. 2015; Orru, Ebi, and

Forsberg 2017). These reviews identify no studies focused on Canada. In North America, studies of the climate penalty focus on the U.S. Many studies of the climate penalty's effect on human health in the U.S. focus only on ozone-related mortality (Knowlton et al. 2004; Bell et al. 2007; Post et al. 2012; Fann et al. 2015; Alexeeff, Pfister, and Nychka 2016; Wilson et al. 2017) and morbidity (Fann et al. 2015; Sheffield et al. 2011). Some studies of the entire U.S. include mortalities in 2050 (Post et al. 2012; Alexeeff, Pfister, and Nychka 2016; Garcia-Menendez et al. 2015; Tagaris et al. 2009; Sun et al. 2015; Stowell et al. 2017) and 2100 (Silva et al. 2017; Saari et al. 2019) due to $PM_{2.5}$ and ozone. Some global studies do include effects for Canada. For example, Silva et al. (2017) estimates $PM_{2.5}$-related premature deaths of 19,100 (95% confidence interval: 8,490, 47,700) in North America in 2100 under a business-as-usual scenario that assumes significant reductions in pollutant emissions. With pollutant emissions constant, climate change alone yields annual premature deaths related to fine particulate matter and ozone ranging from 25,000-120,000 in the U.S. by 2100 (Saari et al. 2019). Given the relationships between Canada and the U.S. in terms of pollution and population, these studies provide a basis for hypothesizing that Canadians would face thousands of additional annual deaths under climate change by the end of the century. Since Canadians currently experience around 7,100 annual premature deaths associated with air pollution (Howard, Rose, and Rivers 2018), this could represent a significant increase in the public health burden associated with this environmental issue.

2.7 Air Quality Co-Benefits of Reducing the Climate Penalty through Climate Policy

According to many studies, climate policy can result in air quality co-benefits that offset policy costs (West, Fiore, and Horowitz 2012; West et al. 2013; Thompson et al. 2014; Saari et al. 2015; Thompson et al. 2016; Li et al. 2018). Most of these studies only consider co-benefits due to reducing co-emitted pollutants, and do not consider the climate penalty. In part, this is because the effect of the climate penalty is small compared to the effect of co-emitted pollutants (Zhang et al. 2017). It is also because modelling the climate penalty means modelling climate change, which adds extra challenges in terms of expertise and computing power (Saari et al. 2019).

Studies that estimate air quality co-benefits from reducing the climate penalty show that they increase over time as the climate policy takes effect. For example, Garcia-Menendez et al. (2015) found co-benefits of \$8-42/tCO_2e at mid-century more than quadrupled by end-of-century to \$45-207/tCO_2e. A handful of other studies include the effect of the climate penalty (Shindell et al. 2012; Shindell, Lee, and Faluvegi 2016; Anenberg et al. 2012; West, Fiore, and Horowitz 2012; Lee et al. 2016; Fann et al. 2015; Saari et al. 2019). Of these, three studies specifically report co-benefits of reducing the climate penalty (Zhang et al. 2017; Garcia-Menendez et al. 2015; Saari et al. 2019). These studies show that these co-benefits are large, including up to thousands of premature deaths avoided, resulting in trillions of economic benefits worth up to one quarter of climate policy costs (Saari et al. 2019; Zhang et al. 2017; Garcia-Menendez et al. 2015; Fann et al. 2015). These studies are either focused on the U.S., or are global, and do not report specific results for Canada.

3. Data and Methodology

3.1 Methodological Approach

The study involves a global integrated assessment modelling (IAM) system with ensemble simulations. The full modelling framework is called the MIT IGSM-CAM-Chem-BenMAP framework. Each component of the model is described in this chapter.

This thesis applies these previously developed ensemble simulations of the global economy, climate system, and air pollution using the MIT IGSM-CAM-Chem framework, presented in detail elsewhere (Paltsev et al. 2015; Garcia-Menendez et al. 2015; Saari et al. 2019), and described briefly here. The main methodological contribution of this thesis is to validate the air pollution results for Canada, and to develop and apply a Canadian version of the health and economic impacts model, BenMAP.

This chapter describes the existing IAM framework and simulations. It also lists and explains the variety of technical tools used in this thesis. It describes the data gathering and processing required for the health impacts modelling, and the projection of these impacts for future years.

3.1.1 Integrated Assessment Modelling Framework

The air pollution and climate policy cost data used in this study were generated by the MIT Integrated Global System Modelling Framework (IGSM). The MIT IGSM is an internally consistent modelling framework representing the human system and earth system, depicted in Figure 9 (Monier et al. 2018).

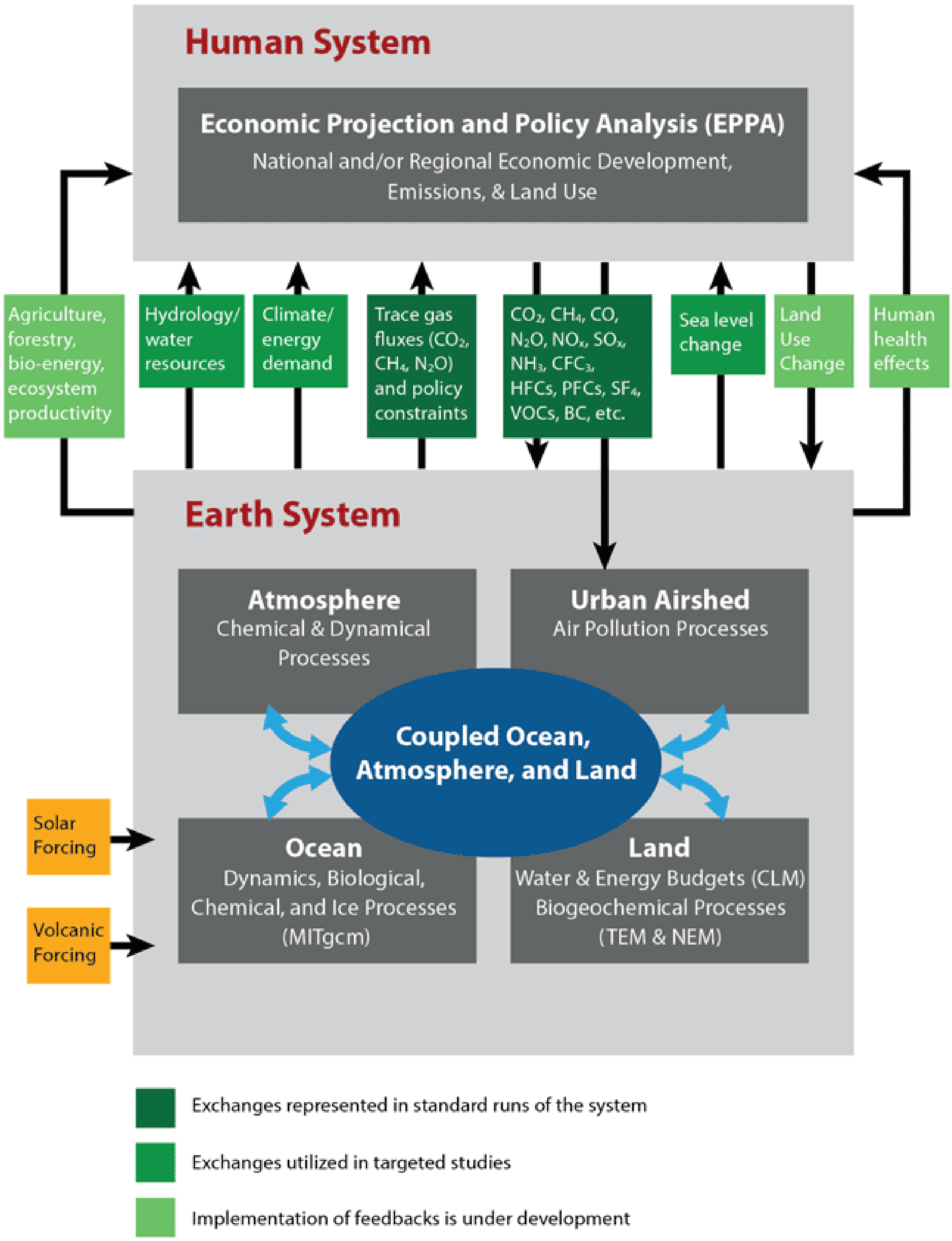


Figure 9. Integrated Global System Modeling (IGSM) Framework from Monier et al. (2018).

The IGSM analysis process starts with running the MIT Economic Projection & Policy Analysis (EPPA) model of the world economy to estimate changes in atmospheric emissions and policy costs, then passing the change in greenhouse gas emissions to the earth system model. The EPPA is a multi-sector, multi-region, computable general equilibrium (CGE) model of the world economy which uses the input-output relationships between sectors from the Global Trade Analysis Project (GTAP) dataset maintained at Purdue University (Paltsev et al. 2015). These are incorporated within a wider social accounting matrix that includes exports, imports, government, expenditure and household demand for final products, and ownership and supply of labour, capital, and natural resources to each sector. The model's basic economic specification is in billions of dollars of inputs (capital rents, labour, resource rents) and gross outputs for each sector in terms of metrics such as energy (exajoules), emissions of pollution (tonnes), land use (hectares), and population (billions of people) (Saari et al. 2019).

Once EPPA is used to implement climate policy, the resulting greenhouse gas emissions are passed to the earth system model. In this case, the earth system model was coupled to the Community Atmosphere Model (CAM) developed by National Center for Atmospheric Research (NCAR) (Lamarque et al. 2012). This version of the IGSM is known as the MIT IGSM-CAM framework, which can generate three-dimensional global climate fields driven by emissions from EPPA (Monier et al. 2013). Global, three-dimensional climate fields under different climate scenarios serve as input to the Community Atmosphere Model with Chemistry (CAM-Chem), which can simulate global atmospheric chemistry. CAM-Chem generates results with a horizontal resolution of 1.9° x 2.5° providing modelled concentrations of O_3 and $PM_{2.5}$, at the ground level.

Then, the modelled concentrations are input to the Environmental Benefits Mapping and Analysis Program − Community Edition (BenMAP-CE) to estimate the associated health and economic impacts. Thus, the MIT IGSM-CAM-Chem-BenMAP framework was used to estimate global policy costs, Canada’s health outcomes, and economic impacts for three scenarios: namely, two policies and a reference case.

3.1.2 Ensemble Simulations

Table 1 describes the experimental conditions and outputs for ensemble simulations used in this study. To filter out noise from natural climate variability, and thus distinguish the effects of forced climate change, numerous simulations were run (for details, refer to Saari et al. (2019)). These simulations are listed in Table 1. The scenarios of interest included a Reference (REF) case, Policy 4.5 (P45), and Policy 3.7 (P37), of which P37 was the most stringent. The policy scenarios were designed in collaboration with the U.S. EPA to align with the Paris Agreement. P45 is similar to Representative Concentration Pathway (RCP4.5), which is meant to represent compliance with the goal of 2°C warming by 2100. P45 complies with the goal under many simulations; however, the mean warming is 2.5°C. Thus, a slightly more stringent scenario was also developed, P37, with a mean warming of 2°C. While the ambitious goal of the Paris Agreement is limiting the increase at 1.5°C, this is an unlikely scenario as the United Nations Environment Programme described it as a goal that "will slip out of reach" in their 2019 report (UNEP 2019). The report describes that going beyond this limit will "increase the frequency and intensity of climate impacts," however, air quality benefits demonstrate a case of diminishing returns with more stringent policy scenarios, as will be shown in the results.

Table 1. Experimental Conditions and Outputs for Ensemble Simulations Used in this Study (adapted from Saari et al. (2019)). EPPA =MIT Economic Projection & Policy Analysis; MESM = MIT Earth System Model; CAM-Chem = Community Atmosphere Model with Chemistry; BenMAP = Environmental Benefits Mapping and Analysis Program; CRF = Concentration-Response Function

Framework	Variables	Simulations	Output
Policy (EPPA) Climate (MESM- CAM) Air Quality (CAM-Chem) Health & Valuation (BenMAP)	Constant: Anthropogenic pollutant emissions Population age/spatial distribution Varying: Population growth Economic growth Baseline mortality incidence rates GHG emissions Climatic conditions Pollution concentrations	Scenarios: Reference, Policy 4.5, Policy 3.7 Years of Interest: 2000, 2050, 2100 Annual Simulations 30-year periods: 1981-2010 2036-2065 2086-2115 5 initializations 150 annual simulations per scenario and year of interest	Impacts Due to $PM_{2.5}$ and Ozone Exposure: - All-cause mortality - Economic valuation of benefits Using CRF: $PM_{2.5}$: - Lepeule et al. (2012) - Krewski et al. (2009) Ozone: - Zanobetti and Schwartz (b) (2008)

Table 2. Three Scenarios Used in Study. As described in Paltsev et al. (2015)

Scenario	Conditions
Reference (REF)	CO_2 reaching 830 ppm, global mean surface temperature increasing by 6° C in 2100
Policy 4.5 (P45)	Total radiative forcing at 4.5 W/m^2, CO_2 reaching 500 ppm, global mean surface temperature increasing by 2.5°C in 2100
Policy 3.7 (P37)	Total radiative forcing at 3.7 W/m^2, CO_2 reaching 460 ppm, global mean surface temperature increasing by 2.0°C in 2100

For the above three scenarios, three target years of interest were set: 2000, 2050, and 2100. For each of these target years, the mean of 150 annual simulations was used to determine the change in air quality in the target year for each given climate scenario. Around each target year, thirty-year periods were considered for each of five different sets of initial conditions. The thirty annual simulations represent interannual variability, and the five different initializations of the climate system capture longer multidecadal variability. For example, in the target year 2000, a thirty-year period of 1981-2010 was considered for each set of five initial conditions resulting in one hundred and fifty annual simulations for each target year. The mean temperature rise for each scenario is included in its description, representing the mean of a distribution of possible temperature rises given climate-related uncertainty (Paltsev et al. 2015).

3.2 Data Gathering

The main methodological contribution of this thesis was to adapt the Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE) for use in Canada. This involved a significant data-gathering and processing exercise, described in this section, while the development of the new model version is described later.

BenMAP-CE is an open-source software developed for the U.S. EPA to analyze national-scale air quality policies. For this research, BenMAP-CE (v. 1.5.0) served as the main tool for analyzing co-benefits, pollution changes, incidences, and economic impacts. It was also used as a visualization tool.

To develop a version of the BenMAP-CE model for Canada (referred to here as BenMAP-Canada), many datasets were gathered and processed. The required data and their connections are described in Figure 10. The variables and their sources are summarized in Table 3.

Table 3. Data Details and Sources.

Data	Year	Sources & References
Population and Mortality	2001	Statistics Canada – Canadian Census https://www12.statcan.gc.ca/english/census01/
Modelled Pollutant Concentrations	2000, 2050, 2100	North Carolina State University – Global CAM-Chem model Courtesy of Fernando Garcia-Menendez
Station Pollution (Ozone)	1980 – 2010	Environment and Climate Change Canada – NAPS http://data.ec.gc.ca/data/air/monitor/national-air-pollution-surveillance-naps-program/
Station Pollution ($PM_{2.5}$)	1995 – 2010	Environment and Climate Change Canada – NAPS http://data.ec.gc.ca/data/air/monitor/national-air-pollution-surveillance-naps-program/
Canada Shapefile	2001	University of Waterloo – Geospatial Centre https://uwaterloo.ca/library/geospatial/
Health Impact Functions	N/A	EPA Standard Health Functions (U.S. Environmental Protection Agency 2017)

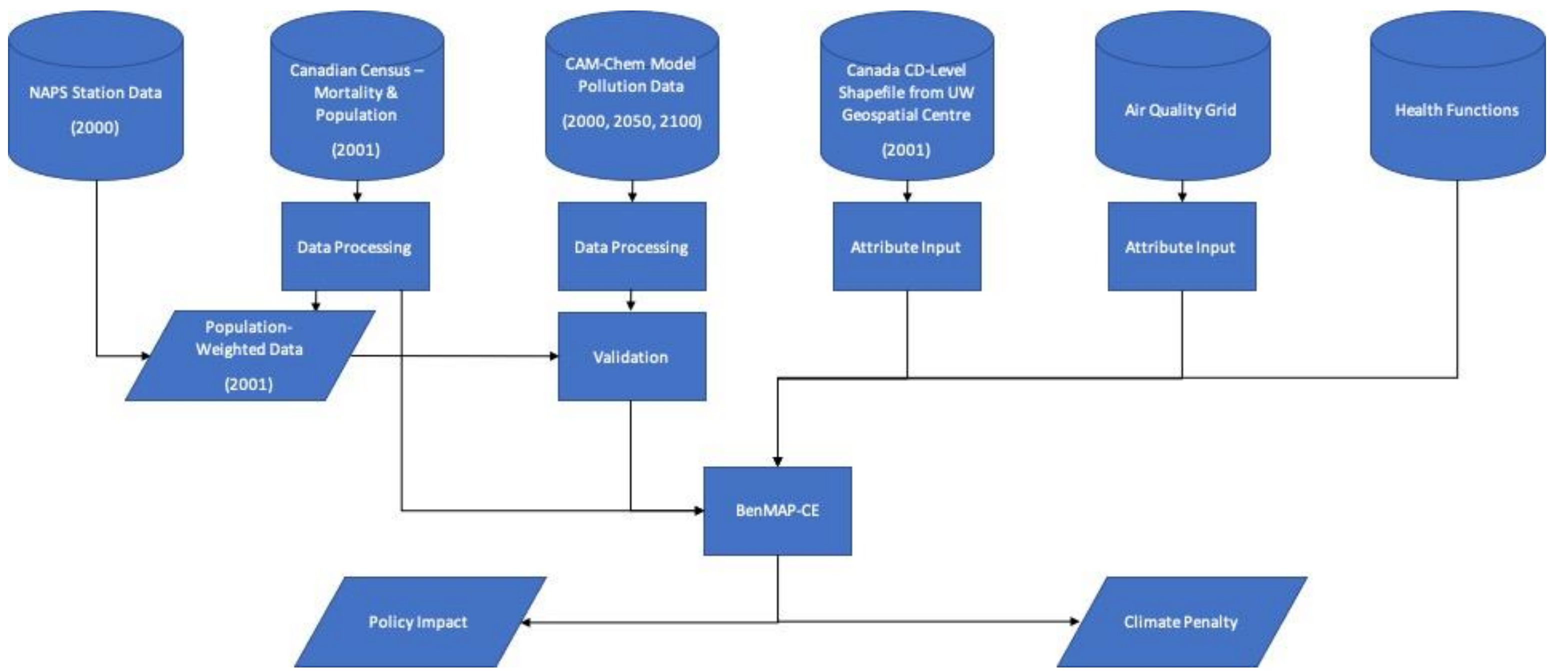


Figure 10. Schematic of Data and Methodology. Sources are shown at the top, followed by the processing steps taken to be input to BenMAP, resulting in the outputs for policy impact and climate penalty.

3.2.1 Technical Tools

Various technical tools were used in the extraction, processing, analysis, and visualization steps of the research, including MATLAB, Excel, Python, and QGIS. MATLAB was the programming language and software used to read the air quality model output files in *.nc* format and to process them into *.csv* files for reading in Python, Excel, and BenMAP. Microsoft Excel was used to visualize and edit the datasets as they were retrieved. Simple calculations and data manipulations with relatively small datasets were performed using Excel.

Python was the programming language used to process the data into the appropriate BenMAP-ready format. Python modules such as Pandas and NumPy were used throughout the data processing steps, along with Sublime Text and Terminal for writing, troubleshooting, and executing the codes. Python was also used along with GeoPandas and MatPlotLib for air quality visualizations over Canada.

QGIS was the open-source GIS software used to edit the Canadian census division-level shapefile and to create the air quality grid, with each of their appropriate attribute tables to be input to BenMAP.

3.2.2 Canada Shapefile

The 2001 census division shapefile for Canada was retrieved through the Geospatial Centre at the University of Waterloo, provided in Figure 11. A second Canada shapefile which shows only the national, provincial, and territorial boundaries, used for visualization, was retrieved from Statistics Canada and edited on QGIS to be in the appropriate format.

Figure 11. Census Divisions of Canada (2001). This shapefile was used to assign mortality and population values at the census division level.

3.2.3 Population and Mortality

The census division-level age-stratified population data and provincial age-stratified mortality data were retrieved from Statistics Canada's archive of the 2001 Canadian census. This year was chosen over data for 2000 – the year for the model data – as the census data for 2001 was assumed to be higher quality and readily available than projected data for year 2000.

3.2.4 Air Quality Grid

A shape file representing the air quality grid over Canada was created using QGIS in accordance with the modelled pollution data from CAM-Chem. The model outputs were provided over a global grid. MATLAB was used to extract the Canadian portion of the domain between latitude and longitude bounds over the populated portion of Canada as shown in Figure 12. It fully encloses Canada from the West, South, and East. In the North, it extends to the base of Ellesmere Island. The grid has a resolution of 1.9° x 2.5°.

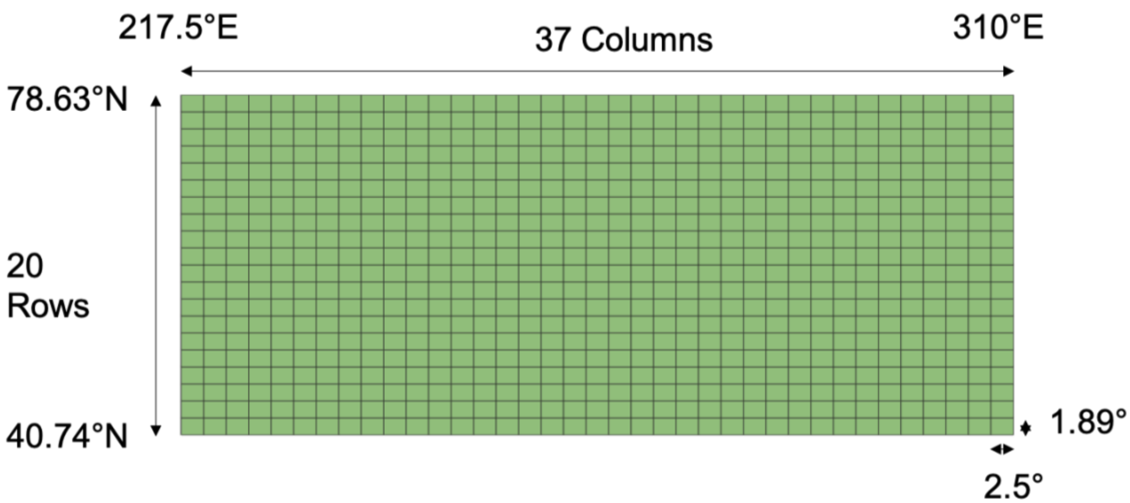


Figure 12. Air Quality Grid Definition. The shape file was created on QGIS on the global grid and the Canadian portion of the domain was extracted between latitude and longitude bounds over the populated portion of Canada.

3.2.5 Modelled Air Pollution

Global air pollutant concentrations were provided by Fernando Garcia-Menendez based on simulations developed for previous studies (Garcia-Menendez et al. 2015; Garcia-Menendez, Monier, and Selin 2017; Pienkosz et al. 2019; Saari et al. 2019). For this study, the Canadian pollution data extracted from the air quality model were comprised of eighteen datasets listed in Table 4. Each dataset contained concentrations for each cell in the air quality grid. The concentrations were the mean of 150 annual simulations used to filter out natural variability. For ozone, the daily 8-hour max was used as the main metric in units of ppb, while $PM_{2.5}$ used the daily 24-hour mean in units of μg/m^3. NO_2 concentrations were not available for use at the time of this study.

Table 4. Air Pollution Datasets. Three scenarios, two pollutants, three years were combined to create a total of 18 datasets.

Scenario	Pollutant	Year
Reference	Ozone $PM_{2.5}$	2000 2050 2100
P45	Ozone $PM_{2.5}$	2000 2050 2100
P37	Ozone $PM_{2.5}$	2000 2050 2100

3.2.6 Station Pollution

The monitoring station data used to validate the modelled pollution data was retrieved from the National Air Pollution Surveillance (NAPS) Program. NAPS was established in 1969 to monitor and assess the quality of ambient air in the populated regions of Canada (Environment and Climate Change Canada 2020c). Air samples are collected at regular frequencies by NAPS for later laboratory analyses. The source for this monitoring station data is Environment and Climate Change Canada.

NAPS hourly monitor data for each pollutant was available as shown in Table 5. As fine particulate matter was not considered until 1995, there were less stations that have measurement data for the pollutant. These numbers of stations are only stations that contributed to the validation, after removing stations with unavailable data and one station that was located near the north pole as it was out of the air quality bounds of the study.

Table 5. NAPS Data Details. Hourly data was available for each day in the year in units of μg/m^3 and ppb, for $PM_{2.5}$ and ozone, respectively.

Pollutant	# of Unique Stations	Years
$PM_{2.5}$	253	1995 – 2010
Ozone	352	1980 – 2010

Figure 13 shows the number of stations available over the validation period for each pollutant. The number of $PM_{2.5}$ monitoring stations grew rapidly from just one in Chilliwack, B.C. in 1995 to 140 stations by the end of 2010, with a total of 253 unique stations throughout the period in between. On the other hand, ozone has 60 monitoring stations in 1980, growing to 212 stations in 2010. This creates a bias in the station data in representing mean concentrations across the study period, where recent decades have more data from more locations than earlier years. This is a limitation to the data availability which is discussed in 5.1 Limitations.

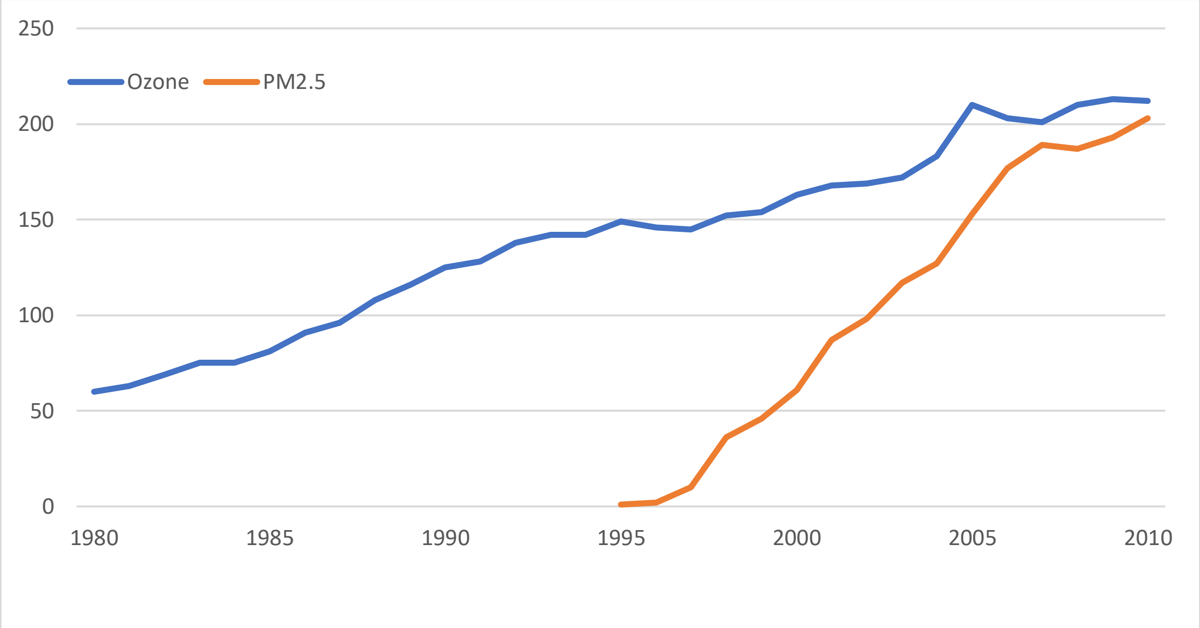


Figure 13. Number of Stations under NAPS Per Pollutant Per Year. Ozone continuously increased since 1980 while $PM_{2.5}$ rapidly increased since 1995.

There was also missing data indicated by "-999" values in the NAPS dataset. The stations with no available data were removed. If each row of the daily monitor measurements for a specific station had no data available, those rows or days for that station were not considered. However, when there was missing data within the period for calculating the pollutant concentration metric – 8 hours for ozone and 24 hours for $PM_{2.5}$ – the metrics were calculated without the missing values. Therefore, some daily 24-hour mean may be calculated with less than 24 hourly measurements, but still consider a span of 24 hours. Similarly, some daily 8-hour max may be calculated with less than 8 hourly measurements, but still consider a span of 8 hours.

3.2.7 Health Impact Functions

The health impact functions used for the study were retrieved from the EPA Standard Health Functions database in BenMAP. The functions used to estimate excess premature all-cause mortality were: Zanobetti and Schwartz (b) (2008) for ozone, and Krewski et al. (2009) and Lepeule et al. (2012) for $PM_{2.5}$. These functions were selected based on their frequent and recent application in the literature in North American health impact assessment (Fann et al. 2021).

The health impact function for ozone by Zanobetti and Schwartz is a 2008 study for air pollution-related mortality in nine cities across the United States during the warm season (May to September) from 1999 to 2002 (Zanobetti and Schwartz 2008). One of the health impact functions for fine particulate matter by Krewski et al. (2009) is based on a reanalysis of the American Cancer Society prospective cohort study. This is an ongoing study on mortality in adults of at least 30 years of age, regarding particulate matter air pollution that started in 1982 which contributed to the setting of the U.S. National Ambient Air Quality Standards (Krewski et al. 2009). Lastly, Lepeule et al. (2012) provides the other health impact function for $PM_{2.5}$ through a study of adults, of age 25 and over, from 1974 to 2009 in six U.S. cities called the Harvard Six Cities Study (Lepeule et al. 2012). Lepeule et al. (2012) estimates are expected to be about double the values of Krewski et al. (2009). The relative risk of the Harvard Six Cities Study is 1.14, while the relative risk of the American Cancer

Society study is 1.06. This implies that, with a linear dose-response approximation, excess risk using the Harvard Six Cities would be 14/6 times higher than using the American Cancer Society study, or nearly double. The difference in relative risk is attributed to the differences in the study designs, as explored in the reanalysis of both studies by the Health Effects Institute (Krewski et al. 2000). Each of the health impact functions for $PM_{2.5}$ are used in health impact analysis, particularly in U.S. regulatory impact assessment. Here, results from each health impact function are included and discussed in parallel to represent uncertainty in the health response to exposure.

Table 6. Health Impact Functions. The three BenMAP-provided EPA Standard Health Functions were used.

Endpoint	Pollutant	Metric	Study Author	Year	Age
All-Cause Mortality	Ozone	D8HourMax	Zanobetti and Schwartz	(2008)	0-99
All-Cause Mortality	$PM_{2.5}$	D24HourMean	Krewski et al.	(2009)	30-99
All-Cause Mortality	$PM_{2.5}$	D24HourMean	Lepeule et al.	(2012)	25-99

3.3 Data Processing and Validation

Many of the data above needed to be processed to their BenMAP-appropriate formats. Below are some of the key processes for reproducibility.

3.3.1 Population and Mortality

The population and baseline mortality rate data needed to be compiled, filtered, edited, and processed into the format ready for input to BenMAP. Python’s data manipulation and analysis tool, Pandas, was used extensively, along with NumPy, to perform the necessary calculations for baseline mortality rates using the deaths and population census data.

As the provincial mortality data divided into more age groups than BenMAP expects, Pandas on Python was used to aggregate and align the ranges of age groups by summing the containing ages, resulting in ten age groups:

- 0 to 4
- 5 to 14
- 15 to 19
- 20 to 24
- 25 to 44
- 45 to 54
- 55 to 64
- 65 to 74
- 75 to 84
- 85 and up

As census division-level mortality was unavailable, provincial and territorial mortality data to approximate the census division level mortality. Age-stratified census division-level mortality rates were approximated by the age-stratified mortality rate of the province or territory:

$$Baseline\ Mortality\ Rate_{CD,i} \approx Baseline\ Mortality\ Rate_{Province(CD),i}$$

$$= \frac{Deaths_{Province(CD),i}}{Pop_{Province(CD),i}}$$

Where:

Baseline Mortality Rate$_{CD,i}$ is the number of deaths in the CD divided by the total population of the CD for the age group *i*, in units of deaths per persons

Baseline Mortality Rate$_{Province(CD),i}$ is the number of deaths in the province or territory containing the CD divided by the total population of the province for the age group *i*, in units of deaths per persons

Deaths$_{Province(CD),i}$ is the number of deaths in the province or territory containing the CD for the age group *i*, in units of deaths, and

$Pop_{Province(CD),i}$ is the number of persons in the province or territory for the age group i, in units of persons.

3.3.2 Modelled Air Pollution Concentrations

The modelled air pollution data in MATLAB output files were already ready for BenMAP input, courtesy of Fernando Garcia-Menendez (Garcia-Menendez et al. 2015). However, the modelled concentrations first needed to be validated by comparison with data from monitor-based observations in Canada.

The available NAPS data by ECCC were used as the monitor data to compare with the model data. The data was processed to remove unavailable data, as well as one station located near the north pole that was out of the air quality grid limits. The hourly measurements were then processed to output the daily 24-hour mean and daily maximum 8-hour average, for $PM_{2.5}$ and ozone, respectively. Then, the mean of concentrations from all monitoring stations across Canada in the relevant period was compared to the national population-weighted modelled average concentrations for each pollutant.

The population-weighted average (PWA) concentration is used to measure the Canadian Environmental Sustainability Indicators (CESI) by ECCC as it is a more robust way of comparing model data with monitor data, due to the high density of monitoring locations in high-population, high-emission, urban areas (Statistics Canada 2015). Population-weighting is also used in the literature for comparing modelled concentrations to station-based concentrations (Pienkosz et al. 2019). The PWA of model data was calculated for the year 2000 (average of years 1981 to 2010), using the population data from the 2001 Canadian census following the equation below:

$$PWA = \sum_{Grid\ Cells} \frac{Population_{Cell}}{Population_{Total}} * Concentration_{Cell}$$

Where:

PWA is the population-weighted average, in units of ppb or µg/m^3

$Population_{Cell}$ is the population in the specific cell, in units of persons

$Population_{Total}$ is the total population of Canada, in units of persons, and

$Concentration_{Cell}$ is the concentration of the pollutant in the specific cell, in units of ppb or $\mu g/m^3$.

The population of each grid cell was retrieved by running a simulation on BenMAP-CE. A function called *Create* c*rosswalks* was used on BenMAP, which calculates the percentage overlap between one grid definition with another, then creates a percentage file that relates the data at one spatial scale to another (U.S. Environmental Protection Agency 2017). Crosswalks were created to relate the population of the census division shape file to the air quality grid shape file.

3.3.3 Canada Shapefile

The retrieved Canada shapefile was processed using QGIS for two major modifications. The original file was in higher definition with multiple polygons for each census division. QGIS was used to *dissolve* the polygons at the census division to align it with the population and mortality data. Next, the attribute tables were created to include the appropriate rows and columns corresponding to the air quality grid.

3.4 BenMAP Modelling

3.4.1 BenMAP-Canada Setup

BenMAP-CE is designed by the U.S. EPA for use in the U.S. This work introduces the process for its use in Canada, under the BenMAP-Canada setup. Figure 14 shows a screenshot from the BenMAP-Canada setup, with the necessary data input.

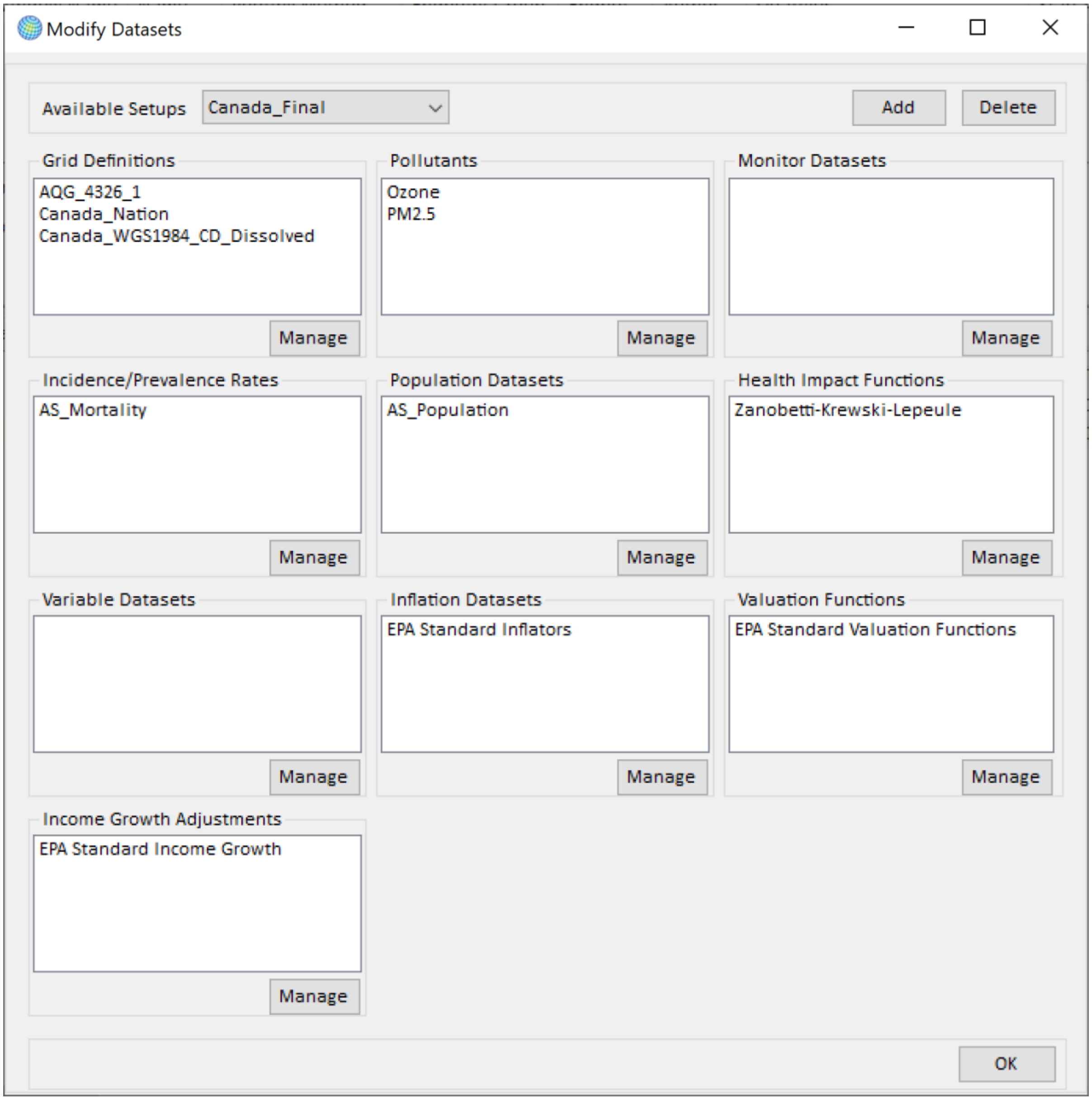


Figure 14. BenMAP-CE Canada Setup. Screenshot from BenMAP-CE under Modify Datasets with the necessary data input for Canada analysis.

Under Grid Definitions, there are three shape files: AQG_4326_1, Canada_Nation, and Canada_WGS1984_CD_Dissolved. The AQG_4326_1 file is used as the air quality grid, as defined above on Figure 12. The modelled air quality data was assigned to this shape file with their appropriate rows and columns. The Canada_WGS1984_CD_Dissolved file is the 2001 census-division shape file of Canada. The original file was retrieved from the

Geospatial Centre at the University of Waterloo, which was then modified using QGIS to only include census divisions, then re-projected onto World Geodetic System 1984 (WGS1984) by BenMAP-CE. The population and mortality data were defined by census divisions; hence the data were assigned to their appropriate census division on the shape file using the census division unique identifier (CDUID), which is a unique identification attribute for each census division. This file was then processed into a single polygon of the entire nation, instead of one polygon per census division using GeoPandas on Python, and the Canada_Nation shape file was created. This shape file was used to aggregate the valuation and mortality results over the entire nation, rather than having separate results for each census division or air quality grid cell. A function called "Create Crosswalk" was used to calculate the percentage overlap that relates one spatial scale to another, which allows calculations between the different shapefiles.

Under pollutants, ozone and $PM_{2.5}$ were defined following the United States' setup, with their Pollutant Metrics as D8HourMax and D24HourMean, respectively. As this study does not consider seasonal metrics, they were not defined for convenience, but can easily be added in the future if necessary.

The Population Datasets category includes the AS_Population dataset which is the age-stratified census division level population data from the 2001 census. This data was retrieved from Statistics Canada and processed as an Excel file (.xlsx), including necessary columns of data such as Race, Ethnicity, Gender, Age Range, Column, Row, and Value. These column definitions are as required by BenMAP-CE and further details can be found on the BenMAP-CE manual (U.S. Environmental Protection Agency 2017). The "Column" column was used to indicate the CDUID of each row of data, as the shape file for this data (Canada_WGS1984_CD_Dissolved) is not in grid format.

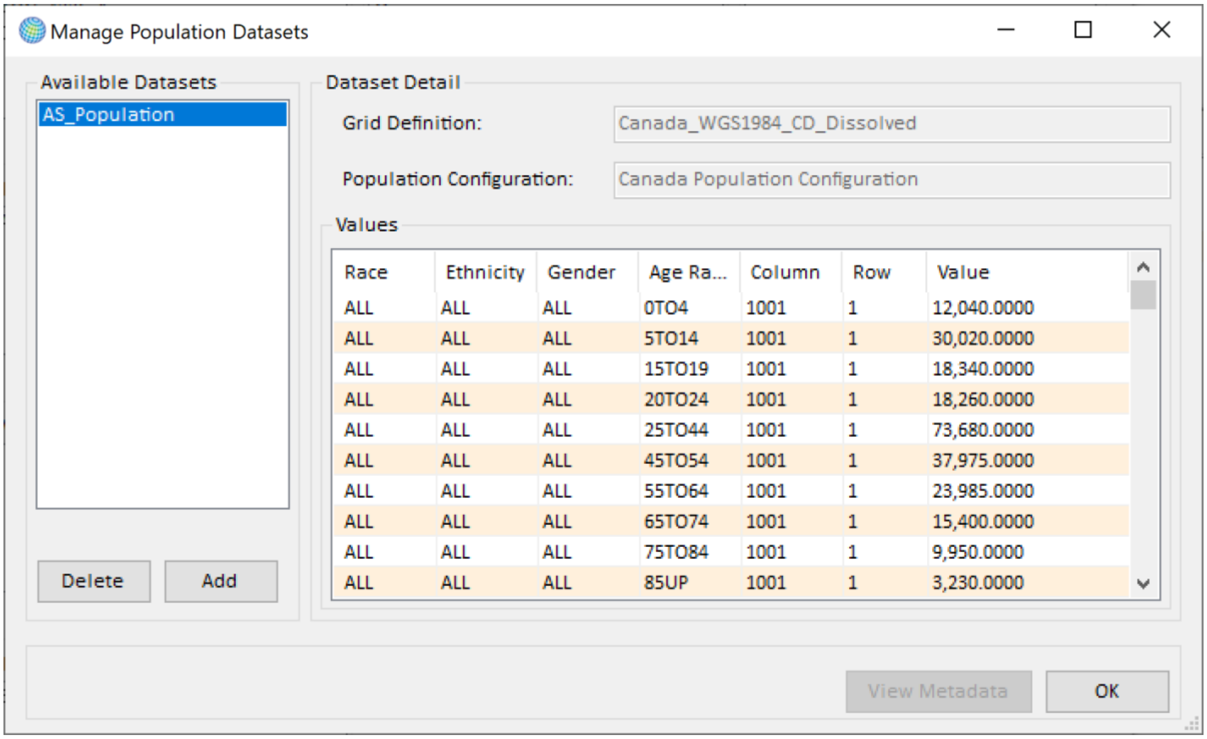


Figure 15. Manage Population Datasets Window Screenshot from BenMAP-CE Canada Setup.

Incidence/Prevalence Rates includes the dataset called AS_Mortality. The age-stratified data divided the baseline mortality by age groups as shown in Figure 16. This was input from an Excel file (.xlsx), including necessary columns of data such as Endpoint, Type, Race, Ethnicity, Gender, Start Age, End Age, Row, Column, and Value, as required by BenMAP-CE (U.S. Environmental Protection Agency 2017). The “Column” column was used as done with AS_Population where the CDUID was indicated rather than their actual row and column as this data does not apply to a grid. This dataset was estimated through the provincial and territorial mortality rate for each age group (AS_Population from above). The provincial and territorial mortality rate dataset from the 2001 Canadian census (Table:13-10-0710-01) was retrieved through Statistics Canada, which provided the mortality rate per 1,000 population for 21 age groups for each province and territory.

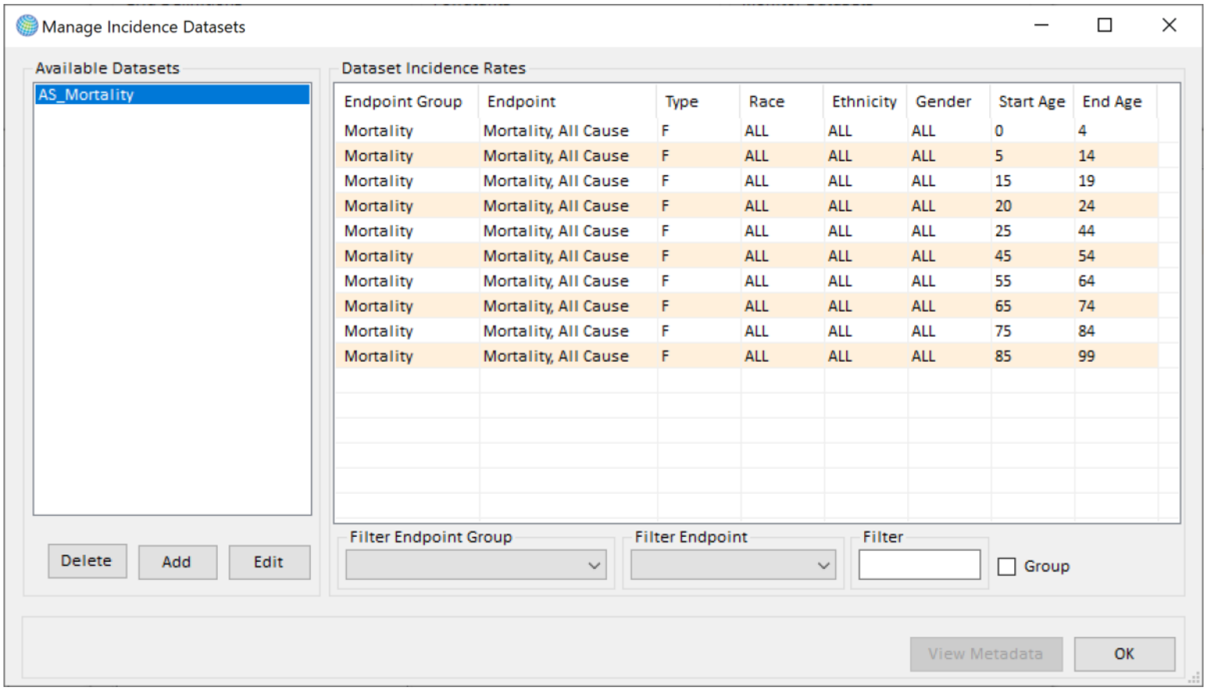


Figure 16. Manage Incidence Datasets Window Screenshot from BenMAP-CE Canada Setup.

The Health Impact Functions were narrowed down from the default EPA Standard Health Functions dataset provided by the U.S. EPA. Three health impact functions were defined and loaded for this study: Zanobetti et al. (2008), Krewski et al. (2009), and Lepeule et al. (2012). The default datasets provided by the U.S. EPA were used for the categories of: Inflation Datasets, Valuation Functions, and Income Growth Adjustments.

3.4.2 BenMAP-Canada Steps

The overall steps for analysis in BenMAP were taken as below:

1. Pollutant Definition
   a. Ozone or $PM_{2.5}$
2. Load Air Quality Data: Baseline (Higher pollution scenario) and Control
   a. Pollutant: Ozone or $PM_{2.5}$
   b. Year: 2000, 2050, 2100
   c. Scenario: REF, P45, P37

3. Load Population Dataset
4. Run Health Impact Assessment
5. Run Valuation
6. Export Results

While most of the above steps are straight-forward, some steps are described in more detail. In Step 2. Load Air Quality Data, the modelled pollution data are loaded, with their appropriate columns of Column, Row, Metric, Seasonal Metric, Annual Metric, and Values. The data is input in the way that BenMAP expects, which is the higher pollution scenario as the baseline and the less polluted scenario as the control. This is to ensure that the concentration change is always a decrease, resulting in positive mortality and valuation results.

Within Step 4. Run Health Impact Assessment, the Pooling Method must be determined. This study used the Default Monte Carlo Iterations of 5,000 runs providing a distribution as a result. The mortality and valuation results provide columns for Mean, Standard Deviation, Variance, and Percentile (2.5 to 97.5 for mortality and 0.5 to 99.5 for valuation). When discussing the results for mortality or valuations, the 95% confidence interval follows the mean, indicated by parentheses (e.g., -170 (-250, -94)).

For Step 5. Run Valuation, the Advanced Valuation Settings were determined. For inflation, the base year of 2000 was used, which has the All Goods Index, Medical Cost Index, and Wage Index of 0.73, 0.59, and 0.68, respectively, with 2015 as the reference year with the index values of 1. The valuation function used was the "VSL, based on 26 value-of-life studies" which has a mean VSL value of $8.7 million in 2015 U.S. dollars. Lastly, the Income Growth Adjustments for 2000 were used, with the factors for "Hospital Admissions" and "Outpatient Visits" set at 1.0, slightly greater than the reference year in 1990.

The BenMAP user guide provided by the U.S. EPA can be referred to for a more in-depth guide on BenMAP use, while questions regarding the BenMAP-Canada setup can be forwarded to the authors (U.S. Environmental Protection Agency 2017).

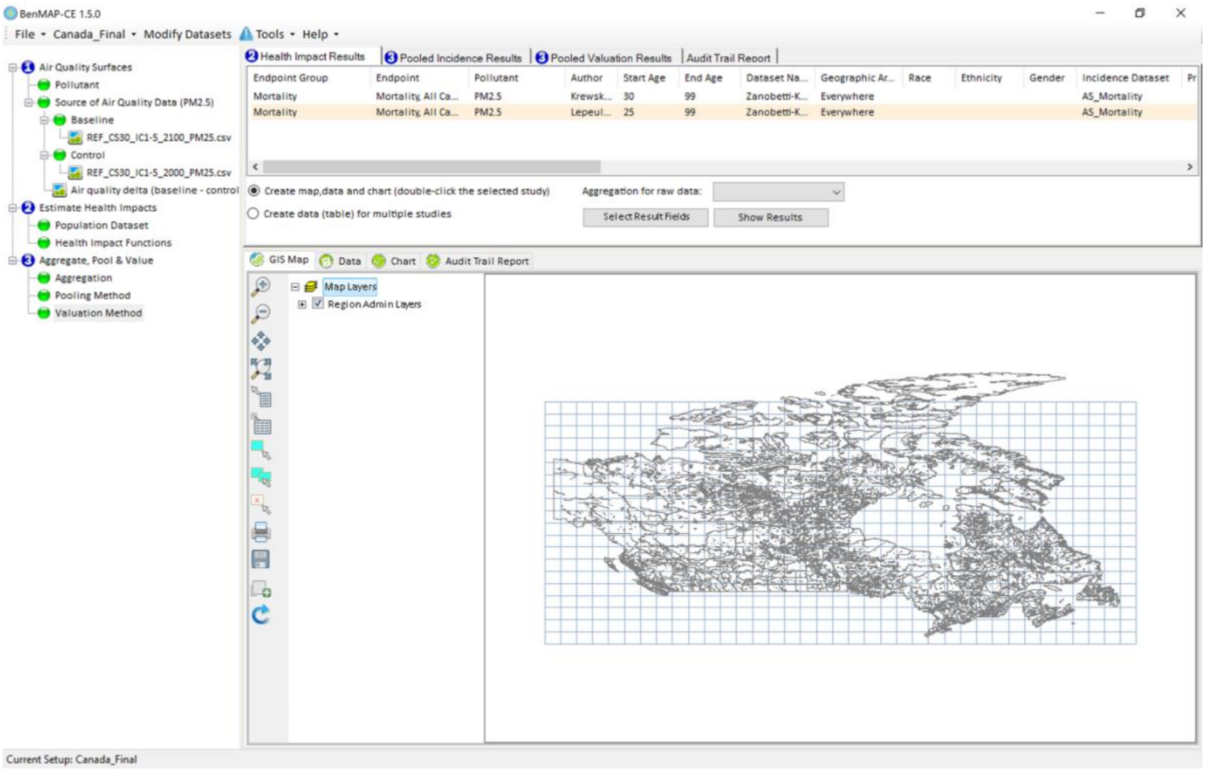


Figure 17. BenMAP-Canada Setup Sample Run Layout. Left column displays the steps of Air Quality Surfaces, Estimate Health Impacts, and Aggregate, Pool & Value. On the right, the Health Impact Results, Pooled Incidence Results, and Pooled Valuation Results are shown which can be visualized on the "GIS Map", or as a spreadsheet under "Data".

3.5 Projection

The incidences of premature death due to pollution exposure from BenMAP were projected for future years 2050 and 2100. The excess premature mortality incidences were projected from the base year of 2000, using the following equation:

$$y_f = y_{2000} * \frac{pop_f}{pop_{2000}} * \frac{y_{o,f}}{y_{o,2000}} = y_{2000} * \gamma_{\text{pop}} * \gamma_o$$

Where:

y_f is the incidences of excess premature mortality in the future, in units of incidence per year

y_{2000} is the base year incidences of excess premature mortality from BenMAP, in units of incidence per year

pop_f is the future year population, in units of persons

pop_{2000} is the base year population, in units of persons

$y_{o,f}$ is the future baseline mortality incidence rate, in units of incidence per year

$y_{o,2000}$ is the base year baseline mortality incidence rate, in units of incidence per year,

The ratios of present values to future values are indicated by γ for population (pop) and mortality incidence rate (o), respectively.

The ratios used to project output from BenMAP to reflect future population and health characteristics are provided in Table 7. The values of future and baseline population and mortality incidence rates were based on projections generated by the MIT EPPA model and International Futures, as retrieved from Paltsev et al. (2015) and West et al. (2013), respectively. The national population values for Canada were those used exogenously in EPPA along with labor productivity to determine GDP growth. The population growth in EPPA is specified as long-run trends based on United Nations data (Paltsev et al. 2005). This approach was taken for consistency with the global scenarios that determined the GHG emissions and policy costs (Paltsev et al. 2015). Table 8 provides the data used for currency conversion, and Appendix G: Projection Dataset includes additional projection data used.

The baseline mortality incidence rates were taken from the International Futures model as provided in West et al. (2013), following the approach used in Garcia-Menendez et al. (2015). Ozone-related risk was primarily associated with respiratory mortality while $PM_{2.5}$-related mortality was dominated by cardiovascular mortality; hence the projection factors were estimated by their respective mortality incidence rates for each future and base year (West et al. 2013).

Table 7. Mortality Incidence Projection Factors and Data Sources

Category	Description	Year	Value	Source
Population Projection	Population Ratio of Year vs. Base Year of 2005	2050	1.35	EPPA modelled population growth based on long-term trends of United Nations Data provided in Paltsev et al. (2015)
		2100	1.50	
Mortality Projection	Baseline Mortality Ratio of Year vs. Base Year of 2008 (Ozone)	2050	1.58	Respiratory Mortality Incidence Rates from International Futures as provided in West et al. (2013)
		2100	2.04	
	Baseline Mortality Ratio of Year vs. Base Year of 2008 ($PM_{2.5}$)	2050	1.50	Cardiovascular Mortality Incidence Rates from International Futures as provided in West et al. (2013)
		2100	1.16	

Table 8. Currency-Related Projection Factors and Data Sources

Description	Value	Source
US 2000 to US 2021	1.55	U.S. Bureau of Labor Statistics www.bls.gov/data/inflation_calculator.htm
US 2005 to US 2021	1.37	
US 2021 to CAD 2021	1.27	Bank of Canada www.bankofcanada.ca/rates/exchange

As for the mortality and population census data, the best available data were used for the base years, which was 2005 from Paltsev et al. (2015). This is a limitation to the analysis and may cause a slight underestimation in the effects over time. However, the error is not expected to be significant as it is a scaling factor for projection only while the difference is relatively small compared to the overall span of a century.

1.1.1.1.1.1 Similarly, the economic valuations were projected for the future years of 2050 and 2100. As the valuations were estimated based on excess incidences of premature mortality, the same conversion was also performed for valuation to reflect future health and demographics, followed by conversion of the valuation from the base year 2000 to the future years by factoring in the changes in GDP and population, as well as income elasticity. Income elasticity is defined as the sensitivity of the VSL to a change in real income, in this case represented as GDP per capita. The equation is as follows:

$$\mathrm{VSL}_{\mathrm{C,F}} = \mathrm{VSL}_{U,2000}\left(\frac{\mathrm{GDP}_{\mathrm{C,F}}}{\mathrm{Pop}_{\mathrm{C,F}}} \Big/ \frac{\mathrm{GDP}_{C,2000}}{\mathrm{Pop}_{C,2000}}\right)^{\mathrm{IE}}$$

Where:

VSL is the valuation, in units of reference dollars

Subscript *C* is for Canada

Subscript *U* is for United States

Subscript *F* is for future

Pop is the population, in units of persons

GDP is the gross domestic product, in units of reference dollars, and

IE is the income elasticity, which is unitless.

The GDP and population values were retrieved from Paltsev et al. (2015) and shown in Table 9. Two cases of income elasticity were studied, with values of 0.4 and 1.0. The income elasticity value of 0.4 was used to demonstrate the central estimate in BenMAP-CE, while the income elasticity of 1.0 is the high estimate in BenMAP-CE for premature mortality (US EPA 2012). These values were then converted from 2000 U.S. dollars to 2021 Canadian dollars for better interpretation of the amount, as well as relevance to Canadian policy.

Table 9. GDP values from EPPA model within the MIT-IGSM from Paltsev et al. (2015). Values are in billions of 2005 U.S. dollars.

Description	Year	Value
U.S. GDP	2050	37,847
	2100	86,709
Canada GDP	2050	3,056
	2100	7,737

4. Results and Discussion

The results from the study are discussed in this chapter, beginning with the validation of the modelled air pollutant concentrations, followed by the analysis of the climate penalty and policy impact of the different policy scenarios. These impacts are compared with the current air quality burden in Canada to provide context: The Lancet Countdown Report for 2018 estimated about 7,100 $PM_{2.5}$-related deaths in Canada for 2015, amounting to around 53 billion Canadian dollars in economic damages (Howard, Rose, and Rivers 2018).

4.1 Model Data Validation

The CAM-Chem air quality model data were validated by comparing with NAPS monitoring station data, as summarized in Table 10. There were 253 NAPS stations considered for particulate matter, while 352 stations were considered for ozone pollution. A total of 413 unique stations were considered. The station data were averaged, resulting in means of 31 ppb and 6.9 µg/m^3 for ozone and $PM_{2.5}$, respectively. The national population-weighted average modelled surface concentrations for 1981 to 2010, for the years available with higher values of 52 ppb for ozone from 1980 to 2010, and 10 µg/m^3 for $PM_{2.5}$ from 1995 to 2010. The mean of the thirty-year modelling period was used, as these data were available. Individual model years within the period were not available for use at the time of this study. This results in a relative error of 66% and 47% for each pollutant, respectively.

Table 10. Summary of Pollution Data Validation. The population-weighted average of the model data for base year 2000 (span of 1981 to 2010 for O_3 and $PM_{2.5}$) compared with station data from NAPS (span of 1980 to 2010 for O_3 and 1995 to 2010 for $PM_{2.5}$).

Data Source	Ozone (ppb)	$PM_{2.5}$ (µg/m^3)
NAPS	31	6.9
Model	52	10
Error (absolute)	20	3.2
Error (%)	66%	47%

A relative percent error of less than 50% is considered to be acceptable performance for $PM_{2.5}$. A recent comparison of CAM-Chem aerosols against observations from a monitoring network in the U.S. called IMPROVE (United States Interagency Monitoring of Protected Visual Environments) shows sufficient agreement for sulphate aerosols and considerable spread for other components (Lamarque et al. 2012). Furthermore, the relative error value of 47% is very similar to the error of 50% from the study of North American air quality, led by the Air Quality Research Division at Environment and Climate Change Canada (Kelly, Makar, and Plummer 2012). Meanwhile, the absolute error of 20 ppb for ozone seems to conform to the study's comparisons of CAM-Chem surface ozone over Eastern U.S. and Europe (Lamarque et al. 2012). Consistent with those findings, surface ozone is overestimated over the Canadian domain. These two studies used for modelled data validation are from the Atmospheric Chemistry and Climate Model Intercomparison Project, designed to compare and characterize air quality and climate change interactions (Lamarque et al. 2012; Kelly, Makar, and Plummer 2012). Furthermore, Lamarque et al. (2012) specifically evaluated the CAM-Chem model globally. While this demonstrates the existence of biases in the model, their importance is diminished when the relative difference in concentrations is studied, rather than the absolute values.

There is a temporal bias in the NAPS station data as well. The number of stations providing measurements for both pollutants increase over their time periods, as shown in Figure 13. There are significantly more stations providing data for latter half of the 30-year period than the earlier half, especially for $PM_{2.5}$ which only started gathering data in 1995. Therefore, the validation data are a potentially biased estimate of the modelled 30-year mean, which could explain some of the difference between the modelled and measured concentrations.

4.2 Climate Penalty

4.2.1 National Average Concentration Changes by Year and Scenario

First, the reference scenario is presented. This provides the effect of the climate penalty, i.e., the effect of climate change on air pollution in the absence of climate policy. Evaluating the difference between present and future air pollutant concentrations provides mixed results between ground-level ozone and particulate matter. For ozone, the national population-weighted average exhibits a decrease in concentration of 0.67 ppb and 0.78 ppb in 2050 and 2100, respectively, as shown in Table 11. Other studies have attributed this decrease to changes in dry deposition rates, humidity, seasonal differences, and natural variability (Racherla and Adams 2006; Silva et al. 2017); however, in this study, the latter factor of natural variability should be minimal.

Conversely, the population-weighted average of fine particulate matter concentration is expected to increase at both mid- and end-of-century, as shown in Table 11. The concentration differences grow from 0.52 $\mu g/m^3$ to 1.3 $\mu g/m^3$ for 2050 and 2100, respectively. Other studies have observed this increase, attributing it to an increase in anthropogenic emissions, as well as climate change-related factors such as biogenic emissions and wildfires (Silva et al. 2017). Here, however, anthropogenic emissions and wildfire emissions are constant, and increases are explained by differing climate impacts on the components of $PM_{2.5}$, including, for example, increasing temperature and water vapor enhancing SO_2 oxidation and thus particulate sulphate (Garcia-Menendez et al. 2015). The decreasing ozone concentration over Canada and the increase in fine particulate matter concentration found here is consistent with recent reviews and multi-model comparisons (Silva et al. 2017; Garcia-Menendez, Monier, and Selin 2017)

Table 11. Population-Weighted Average Climate Penalty for the Reference Scenario in Comparison with the Base Year in 2000.

Scenario	Year	8HMAX O_3 (ppb)	D24HMEAN $PM_{2.5}$ ($\mu g/m^3$)
REF	2000 - 2050	-0.67	0.52
	2000 - 2100	-0.78	1.3

4.2.2 Maps of Concentration Changes under Climate Change Scenarios

Next, the modelled air quality concentrations are plotted across Canada to understand pollutant changes by location. Figure 18 shows the change in ground-level ozone pollution comparing the start-of-century with 2050 and 2100 for the reference scenario. Ozone shows an overall decreasing trend in most of Canada outside of the Greater Toronto Area compared to start-of-century conditions, with the relative change in concentrations growing in 2100. While examining the atmospheric processes are out of the scope of this study, one explanation for the decreasing ozone is the increase in humidity (Kelly, Makar, and Plummer 2012). Increasing humidity is expected to decrease ozone pollution as shown on Figure 8 (Fiore, Naik, and Leibensperger 2015). This decreasing trend is outweighed in highly populated areas, where ozone increases. This decreasing pattern aligns with the population-weighted average above, with an observed decrease for ozone for both 2050 and 2100 for the entire country.

Fine particulate matter pollution responds differently, as shown in Figure 19. Most of the country sees small concentration changes of less than 0.5 $\mu g/m^3$, while southern Canada shows a worsening trend, shown in Figure 20. This is significant as the 2016 Canadian census found 66% of Canadians living within 100 km of the border – an area that represents about 4% of Canada's territory (Statistics Canada 2017). Many metropolitan areas display a cluster of red, including Toronto, Vancouver, Calgary, Edmonton, Montreal, and Québec City. As much of the nation's population reside in these metropolitan urban areas, this translates to an overall increase in pollutant exposure, as seen in the national population-weighted means. The Greater Toronto Area is expected to experience the largest negative impact for both ozone and particulate pollution in 2050 and 2100, while other cities will experience slightly lower ozone concentrations with greater fine particulate matter pollution. In 2016, the $PM_{2.5}$ pollution in Toronto and Montreal were at or exceeding the World Health Organization guideline of 10 $\mu g/m^3$ and the pollution is expected to worsen over time, under business-as-usual scenarios (Anenberg et al. 2019). This increase in fine particulate matter pollution leads to a serious increase in mortality as shown in subsequent analysis. That subsequent analysis is national, given the relatively coarse detail of the air quality and health-related data. However, the concentration maps show that the most important changes are likely to occur over major Canadian cities, and that these drive the national health and economic impacts presented in the following sections.

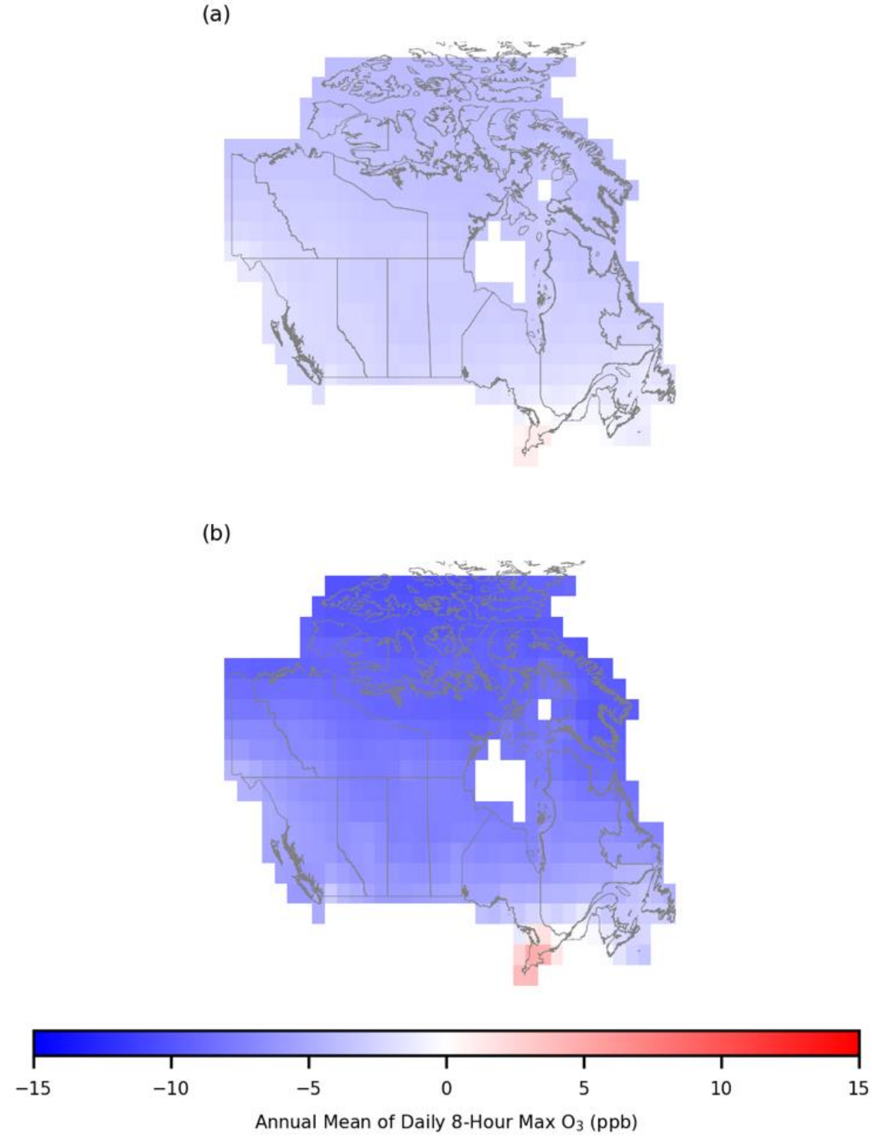


Figure 18. Climate Penalty on Future Ozone. Concentration changes under Reference Scenarios for ground-level ozone (annual mean of daily 8-hour maximum in ppb) compared to start-of-century for (a) 2050 and (b) 2100.

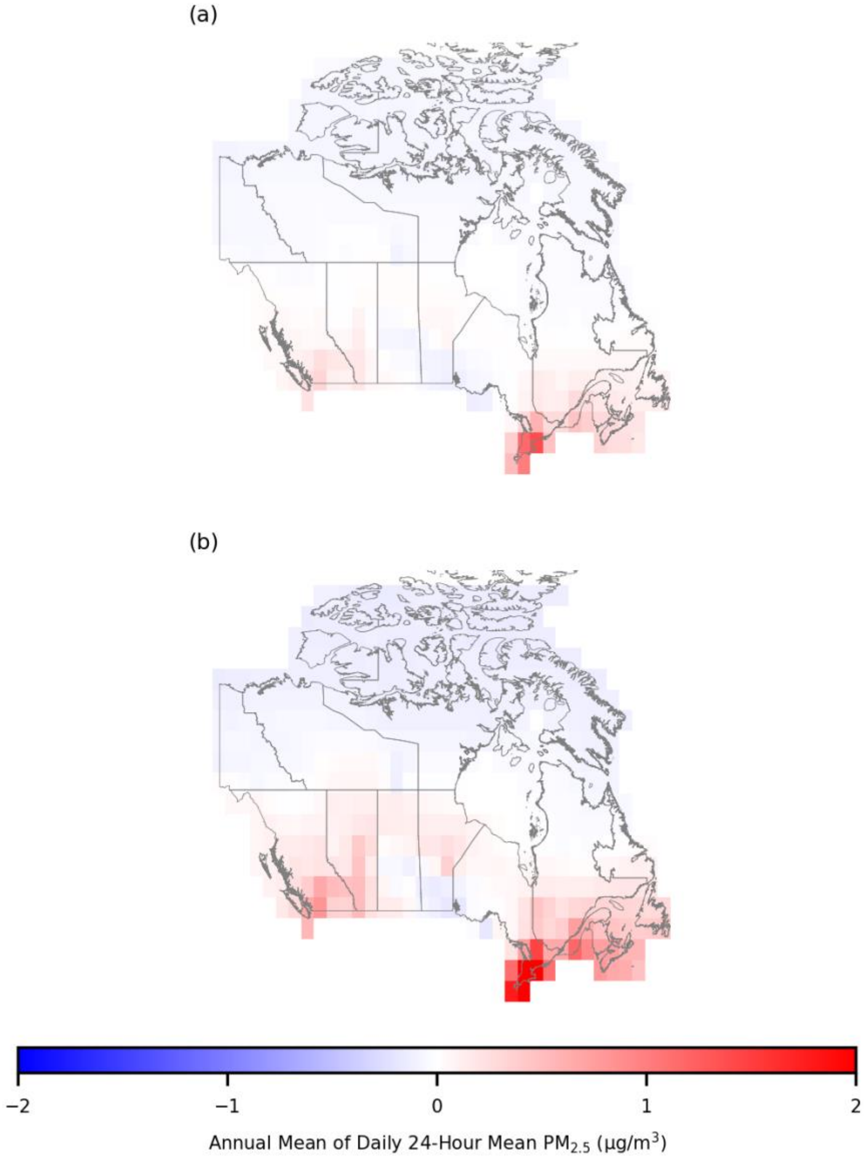


Figure 19. Climate Penalty on Future $PM_{2.5}$. National concentration changes under Reference Scenarios for ground-level $PM_{2.5}$ (annual mean in µg/m^3) compared to start-of-century for (a) 2050 and (b) 2100. Note the scale is restricted to better show the variation.

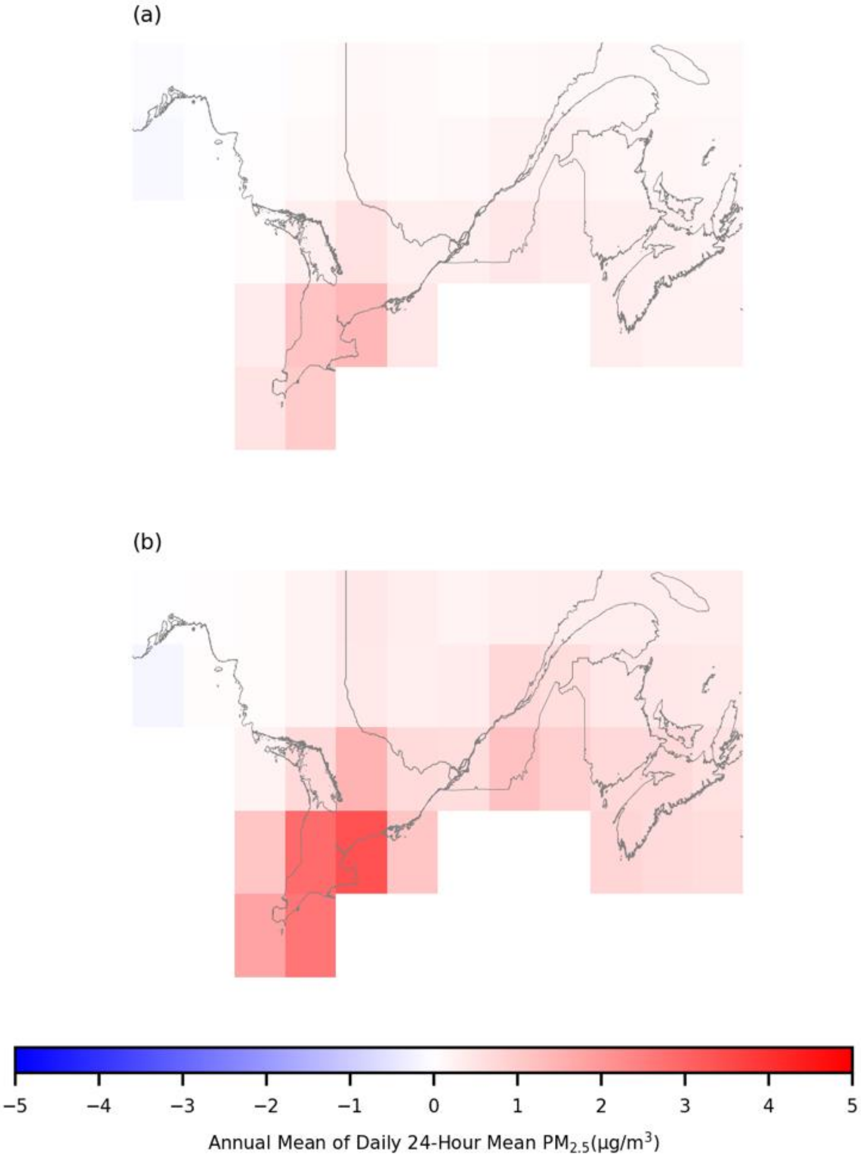


Figure 20. Climate Penalty on Future $PM_{2.5}$ in Southern Ontario. Southern part of Eastern Canada concentration changes under Reference Scenarios for ground-level $PM_{2.5}$ (annual mean in μg/m³) compared to start-of-century for (a) 2050 and (b) 2100. Note the scale for is wider than Figure 19 and contains the maximum concentration increase.

4.2.3 Premature Mortality Associated with Air Pollution by Year and Scenario

The climate penalty in the concentrations shown in the previous section directly relate to increased risk of premature mortality, which implies a higher mortality burden in the future. For a better understanding of the health burden associated with the climate penalty under the reference case, the change in incidences of premature mortality due to ozone and $PM_{2.5}$

exposure between the base year and the future years are tabulated in Table 12. These changes were projected based on population and baseline mortality incidence rates. The un-projected values are provided for reference in Appendix A: Climate Penalty Mortality.

Due to the decrease in ground-level ozone concentrations, incidences of premature mortality due to ozone exposure also decrease slightly. However, the increase in $PM_{2.5}$-related mortality is significant enough to entirely offset the change in ozone. Using the health impact functions of the American Cancer Society Study (Krewski et al. 2009) and the Harvard Six Cities Study (Lepeule et al. 2012) the net increase in annual incidences of premature mortality due to the two air pollutants (and their 95% confidence intervals) are 1,100 (630, 1,600) and 2,800 (1,200, 4,400) for mid-century, respectively, and 2,500 (1,500, 3,500) and 6,200 (2,900, 9,500) for the end of the century, respectively. Table 12 shows the policy impact on future premature mortality in more detail. The upper and lower relative errors of the 95% confidence intervals are tabulated in Appendix H: 95% Confidence Interval Relative Error, approximately 42% around the mean.

These $PM_{2.5}$-related premature deaths in 2100 can be compared with a global study that estimated North American $PM_{2.5}$-related premature deaths of 19,100 (8,490, 47,700) (Silva et al. 2017). While Canada's values are outside of the confidence interval for 2100, this is expected as most North American premature deaths will occur in the United States, which has a larger population and higher average $PM_{2.5}$ pollution.

These results can be placed in the context of the current public health burden associated with $PM_{2.5}$. In this respect, climate change can nearly double the 2015 annual $PM_{2.5}$-related mortality estimate of 7,100 by the end of the century if business continued as usual (Howard, Rose, and Rivers 2018). Meanwhile, in 2016, Toronto's estimated $PM_{2.5}$-related deaths were 1,240, while Montreal and Calgary estimated deaths were 710 and 240, respectively (Anenberg et al. 2019). The urban areas' higher $PM_{2.5}$-related mortality rates are expected to worsen as most of the increased mortality is experienced in areas with the most increase in pollution concentration – especially in $PM_{2.5}$ – which is in the urban areas. Since the health impact functions are not linear, the comparison of mortality impacts between policies with the reference scenarios are studied in the next section assessing the policy impact.

Table 12. Change in Projected Annual Incidences of Premature Mortality Associated with Air Pollution Due to the Climate Penalty. While ozone-related premature mortality is expected to decrease in the future, the $PM_{2.5}$-related premature mortality is projected to increase to more than offset the decrease by ozone. Ozone: Zanobetti et al. (2008); $PM_{2.5}$ (ACS): American Cancer Society Study (Krewski et al. (2009)); $PM_{2.5}$ (Six City): Harvard Six Cities Study (Lepeule et al. (2012)

Scenario	Year	Ozone	$PM_{2.5}$ (ACS)	$PM_{2.5}$ (Six City)
REF	2000 - 2050	-170 (-250, -94)	1,300 (880, 1,700)	3,000 (1,500, 4,500)
	2000 - 2100	-290 (-420, -160)	2,800 (1,900, 3,700)	6,500 (3,300, 9,700)

4.2.4 Economic Impacts of Air Pollution due to Climate Penalty

Using the VSL, premature mortality induced by the climate penalty can be translated into dollars to quantify the climate-related economic impacts, as shown in Table 13 and Table 14. These are projected values, with the raw output from BenMAP provided in Appendix B: Climate Penalty Valuation. Table 13 uses Krewski et al. (2009) as the health function for particulate matter. This is the lower and more conservative option of the two main North American studies linking $PM_{2.5}$ and premature death. For the income elasticity of 0.4, the premature deaths translate to a loss of 16 billion Canadian dollars in 2050 and 45 billion dollars lost in 2100. An income elasticity of 1 increases these estimates to 21 billion dollars and 90 billion dollars, respectively. Table 14 presents the same analysis using Lepeule et al. (2012), with estimates more than doubling for each case.

These economic damages are significant when compared to the current burden of air pollution in Canada. Compared to the estimated 53 billion Canadian dollars lost from $PM_{2.5}$ pollution in 2015 (Howard, Rose, and Rivers 2018), the damages greatly increase in 2100 by a range between approximately two-times and five-times, depending on the income elasticity and health impact study used. As a reference, the gross domestic product of Canada is estimated to be 3.1 trillion and 7.7 trillion 2021 Canadian dollars in 2050 and 2100, respectively (Paltsev et al. 2015). This translates to the climate penalties accounting for a loss between 0.51% and 1.7%, and between 0.58% and 2.9% of the estimated national gross domestic product for 2050 and 2100, respectively. The upper and lower relative errors of the 95% confidence intervals are tabulated in Appendix H: 95% Confidence Interval Relative Error. These distributions are asymmetric with a long upper tail, so that the relative errors are approximately 91% below the mean, and approximately 180% above the mean. The potential gains for reducing mortality are calculated in the following section for quantifying the policy impact.

Table 13. Annual Economic Damages Associated with Premature Deaths from Air Pollution under Climate Change (in Billions of CAD 2021). The aggregation of mortality using Krewski et al. (2009) for $PM_{2.5}$ and Zanobetti et al. (2008) for ozone is presented, with 95% confidence intervals in parentheses, for both income elasticity (IE) scenarios.

Scenario	Projected Valuation IE = 0.4	Projected Valuation IE = 1
REF 2050 vs. REF 2000	16 (1.5, 44)	21 (2, 58)
REF 2100 vs. REF 2000	45 (4.3, 120)	90 (8.5, 250)

Table 14. Annual Economic Damages Associated with Premature Deaths from Air Pollution under Climate Change (in Billions of CAD 2021). The aggregation of mortality using Lepeule et al. (2012) for $PM_{2.5}$ and Zanobetti et al. (2008) for ozone is presented, with 95% confidence intervals in parentheses, for both income elasticity scenarios.

Scenario	Projected Valuation IE = 0.4	Projected Valuation IE = 1
REF 2050 vs. REF 2000	42 (3.7, 120)	55 (4.9, 160)
REF 2100 vs. REF 2000	110 (10, 330)	220 (20, 620)

4.3 Policy Impact

4.3.1 National Average Concentration Changes by Year and Scenario

Next, the impact of policy is studied. This refers to the quantification of the difference between the reference scenario and a policy scenario in the future: The two policy scenarios studied are P45 and P37. The mean concentrations of ozone are expected to increase while the concentrations for particulates are expected to decrease with policy implementation, as shown in Table 15.

Table 15. Population-Weighted Average of Differences in Pollution Concentrations Due to Policy Impact for P45 and P37 Scenarios. Policy impact refers to the difference between the reference scenario and the policy scenarios in future years.

Scenario	Year	8HMAX O_3 (ppb)	D24HMEAN $PM_{2.5}$ (μg/m^3)

REF vs. P45	2050	0.15	-0.25
	2100	0.0086	-0.81
REF vs. P37	2050	0.27	-0.25
	2100	0.58	-0.97

Ground-level ozone concentrations are projected to increase under policy scenarios in comparison to the reference scenario by 0.15 ppb under P45 and 0.27 ppb under P37 in 2050, and 0.0086 under P45 and 0.58 ppb under P37 in 2100. The more stringent P37 scenarios display higher values than P45, as expected, since the more stringent policy has a greater effect on concentrations. The fact that ozone levels increase under policy, when considered alone, may appear to suggest that there are little to no health-related co-benefits to reducing greenhouse gases.

While this may be the case for ozone, the case for fine particulate matter is different. The future concentrations for $PM_{2.5}$ demonstrate a significant decrease in the policy scenarios compared to the reference scenarios (an approximate decrease of 0.8 $\mu g/m^3$ and 1 $\mu g/m^3$ compared to the reference case for P45 and P37, respectively). The differences are 0.25 $\mu g/m^3$ for both policy scenarios in the mid-century, and 0.81 $\mu g/m^3$ under P45 and 0.97 $\mu g/m^3$ under P37 in 2100. While the potential co-benefits are clear in the case for particulate matter, there is a case of diminishing returns for policy stringency in the short term, as the difference between the benefits of P37 and P45 for 2050 is negligible. This implies that the health co-benefits from reducing greenhouse gases do not increase linearly with increasing policy stringency. The benefits are further studied in terms of premature mortality, in a following section.

4.3.2 Maps of Concentration Changes under Future Policy Scenarios

Next, the policy impact is studied geographically. Figure 21 shows that for ground-level ozone, the nation generally experiences an increase in concentrations in comparison to the reference scenario for the same year. The exception is the southern part of Ontario which experiences a decrease in ground-level ozone concentrations in both policy scenarios for mid- and end-of-century. The findings align with the population-weighted average which shows an overall increase in ozone pollution in Canada as the policy impacts for both policy scenarios in 2050 and 2100.

Meanwhile, the change in concentrations of fine particulate matter show a great reduction focussed around the urban areas, as shown in Figure 22. This includes the clusters in southeastern Canada around Toronto, Ottawa, and Montreal, as well as some in the western provinces, in British Columbia and Alberta. The southern Ontario area with the most significant changes is visualized in Figure 23 with its maximum change within the scale of the colour bar.

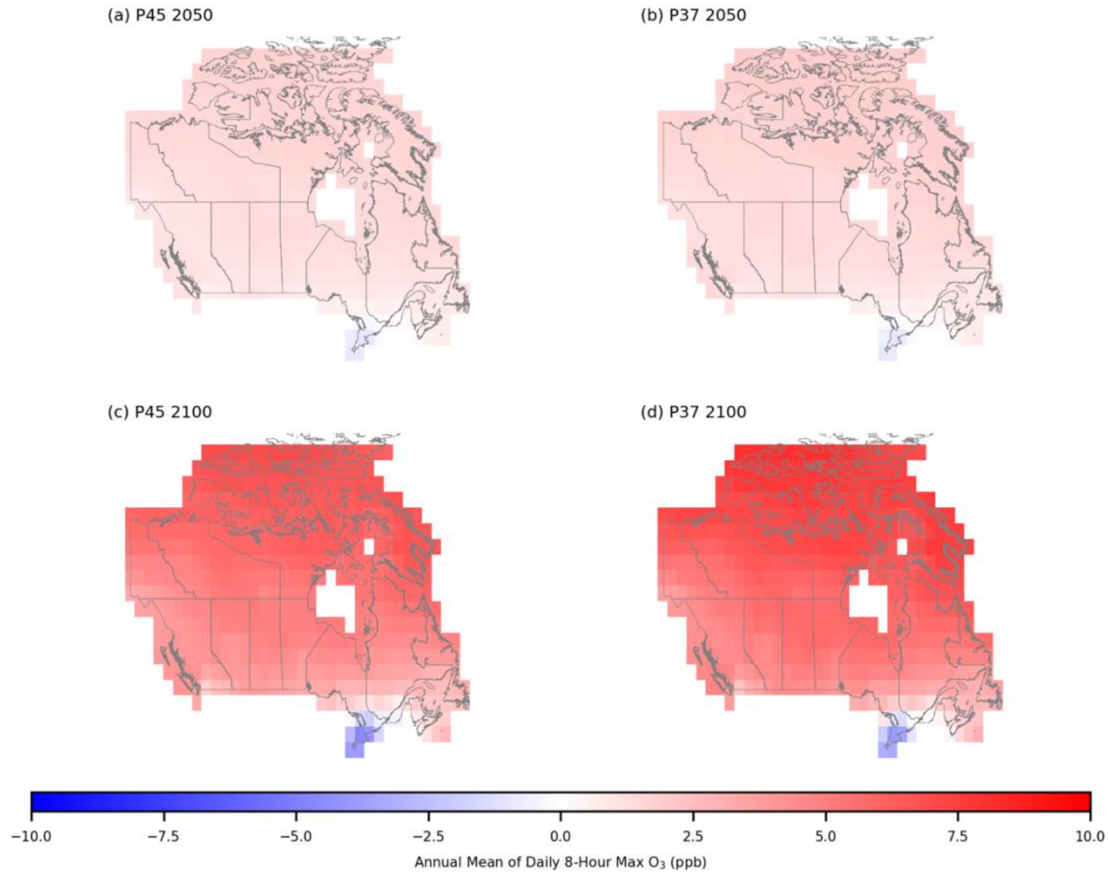


Figure 21. Future Concentration Changes Due to Policy Impact for Ground-Level Ozone. Under both policy scenarios, most of Canada experiences an increase in ground-level ozone concentration except for southern Ontario, around the Greater Toronto Area. The end-of-century shows a more extreme picture of the same trend as 2050. (a) P45 2050 vs. REF 2050; (b) P37 2050 vs. REF 2050; (c) P45 2100 vs. REF 2100; (d) P37 2100 vs. REF 2100.

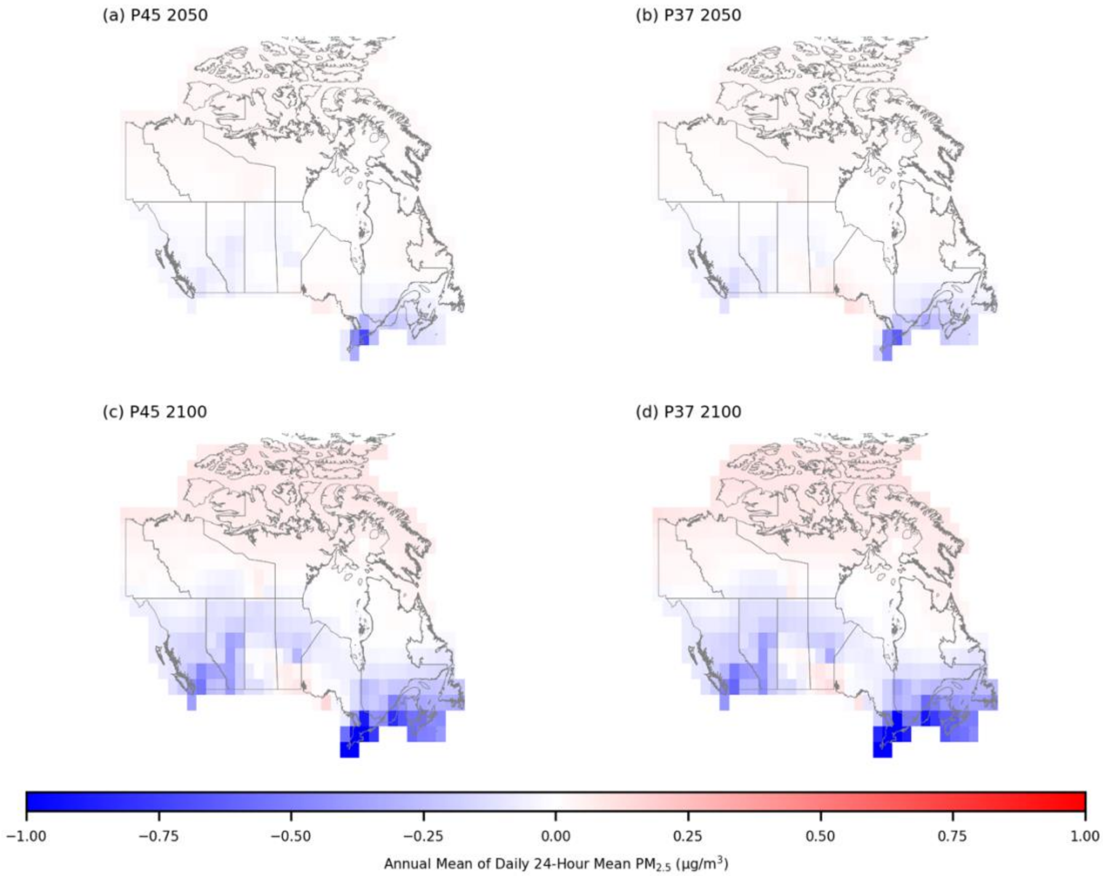


Figure 22. Future Concentration Change in Policy Scenarios vs. Reference Scenarios for Fine Particulate Matter. Under both policy scenarios, most of the policy impacts are experienced in metropolitan areas such as Toronto, Montreal, and Vancouver. Less population-dense areas such as the territories experience slight increases in fine particulate matter under both policy scenarios, more clearly visible at the end-of century. Note the scale is restricted to better show the variation. (a) P45 2050 vs. REF 2050; (b) P37 2050 vs. REF 2050; (c) P45 2100 vs. REF 2100; (d) P37 2100 vs. REF 2100.

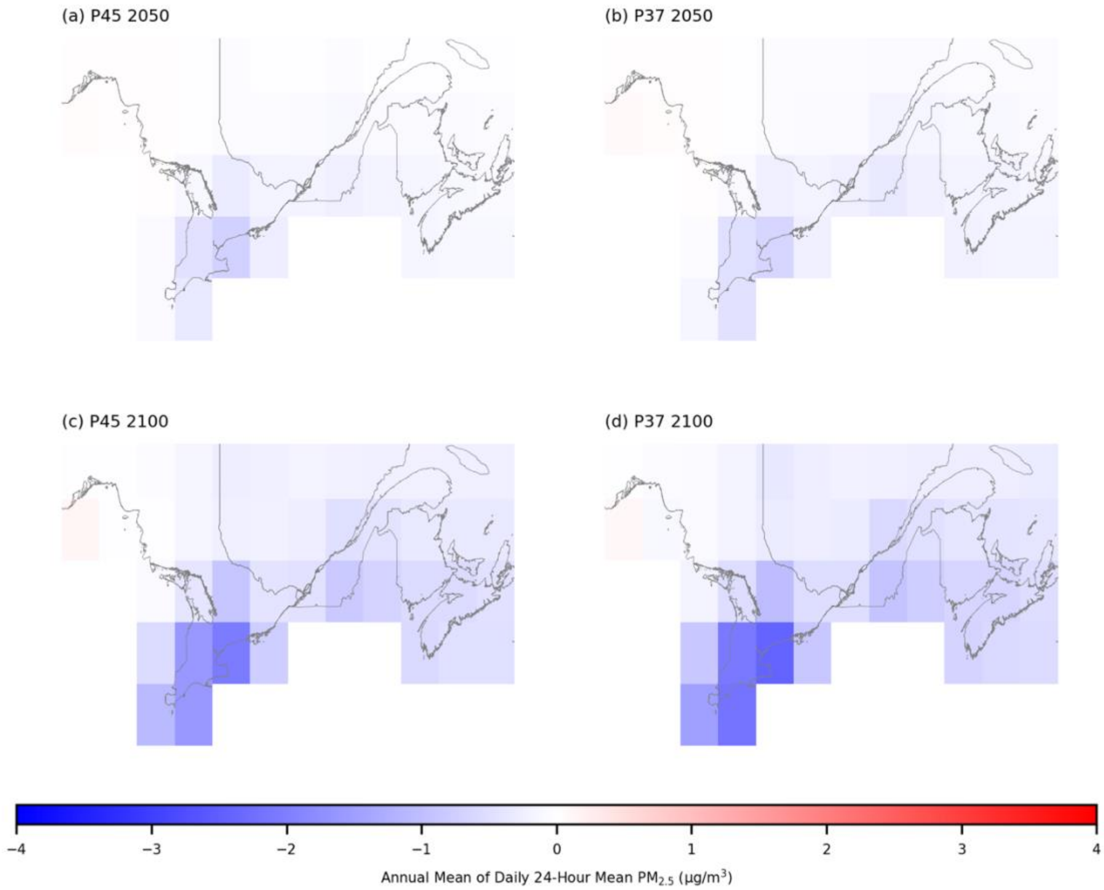


Figure 23. Future Concentration Change in Policy Scenarios vs. Reference Scenarios for Fine Particulate Matter in Southern Ontario. This adjusted scale fully portrays the concentration changes in the Greater Toronto Area. Note the scale for is wider than Figure 22 and contains the maximum concentration decrease. (a) P45 2050 vs. REF 2050; (b) P37 2050 vs. REF 2050; (c) P45 2100 vs. REF 2100; (d) P37 2100 vs. REF 2100

4.3.3 Premature Mortality Associated with Air Pollution by Year and Scenario

The changes in concentrations were used to estimate their effect on premature mortality. As ground-level ozone concentrations increased in policy scenarios in comparison to the reference scenario, it was expected that the premature mortality associated with ozone would also increase in those cases. The national annual mean increases from the reference scenario in ozone-related premature mortality ranged between 42 (23, 62) and 71 (38, 100) at mid-century, and between 20 (12, 28) and 230 (120, 330) premature deaths at end-of-century. The mean differences with 95% confidence intervals can be found in Table 16. (For reproducibility, the un-projected equivalent estimates are in Appendix C: Policy Impact Mortality). Meanwhile, the reduction in premature mortality values related to fine particulate matter were larger by at least an order of magnitude, with their national annual means ranging from 630 (430, 830) to 1,500 (750, 2200) in 2050 and 1,800 (1,200, 2,300) to 5,000 (2,400, 7,200) in 2100. As expected from the concentration difference for policy impact, the total avoided premature deaths were highest for the most stringent policy scenario, using the Harvard Six Cities study (Lepeule et al. (2012)).

Table 16. Change in Projected Premature Mortality Due to Policy Impact. The reduction in premature mortality related to fine particulate matter outweighs the slight increase due to ozone in every scenario. Ozone: Zanobetti et al. (2008); $PM_{2.5}$ (ACS): American Cancer Society Study (Krewski et al. (2009)); $PM_{2.5}$ (Six City): Harvard Six Cities Study (Lepeule et al. (2012))

Scenario	Year	Ozone	$PM_{2.5}$ (ACS)	$PM_{2.5}$ (Six City)
REF vs. P45	2050	42 (23, 62)	-630 (-830, -430)	-1,500 (-2,200, -730)
	2100	20 (12, 28)	-1,800 (-2,300, -1,200)	-4,100 (-6,100, -2,000)
REF vs. P37	2050	71 (38, 100)	-650 (-850, -440)	-1,500 (-2,200, -750)
	2100	230 (120, 330)	-2,100 (-2,800, -1,400)	-5,000 (-7,200, -2,400)

4.3.4 Economic Benefits of Air Pollution Reduction due to Policy Impact

The changes in premature mortality were then converted to economic values using the VSL. Table 17 summarizes the more conservative estimates with Krewski et al. (2009) as the $PM_{2.5}$ health impact function. (Un-projected values from BenMAP are provided in Appendix D: Policy Impact Valuation). The mean policy benefit values range from 6.7 billion Canadian dollars (2021) for P45 with income elasticity of 0.4 to 11 billion Canadian dollars for P37 with income elasticity of 1, for the mid-century. For the end-of-century, the values range from 34 billion Canadian dollars for P45 using income elasticity of 0.4, to 73 billion Canadian dollars for P37 using income elasticity of 1. Table 18 summarizes the higher estimates using Lepeule et al. (2012) as the $PM_{2.5}$ health impact function, which results in valuations approximately double to triple the values from Table 17, as expected.

Table 17. Estimated Economic Benefit of Reduction in Projected Annual Premature Mortality, Converted to Valuation using VSL, in Billions of CAD 2021. The aggregations of mortality using Krewski et al. (2009) for $PM_{2.5}$ and Zanobetti et al. (2008) for ozone are presented, with 95% confidence intervals in parentheses, for both income elasticity scenarios.

Scenario	Projected Valuation IE = 0.4 (Billions CAD 2021)	Projected Valuation IE = 1 (Billions CAD 2021)
P45 2050 vs. REF 2050	8.5 (0.80, 23)	11 (1.0, 30)
P45 2100 vs. REF 2100	34 (3.1, 91)	63 (5.9, 170)
P37 2050 vs. REF 2050	8.3 (0.78, 22)	11 (1.0, 29)
P37 2100 vs. REF 2100	32 (3.0, 87)	66 (6.2, 180)

Table 18. Estimated Economic Benefits of Reduction in Projected Annual Premature Mortality in Billions of CAD 2021. The aggregations of mortality using Lepeule et al. (2012) for $PM_{2.5}$ and Zanobetti et al. (2008) for ozone are presented, with 95% confidence intervals in parentheses, for both income elasticity (IE) scenarios.

Scenario	Projected Valuation IE = 0.4 (Billions CAD 2021)	Projected Valuation IE = 1 (Billions CAD 2021)
P45 2050 vs. REF 2050	21 (1.8, 59)	27 (2.4, 76)
P45 2100 vs. REF 2100	79 (7.0, 220)	150 (13, 420)
P37 2050 vs. REF 2050	22 (1.9, 62)	28 (2.5, 80)
P37 2100 vs. REF 2100	84 (7.4, 240)	160 (14, 460)

4.3.5 Policy Cost Offset

The annual co-benefit of the policy is then compared with the annual cost of implementing each policy in Canada. The policy costs are estimated using the Economic Projection and Policy Analysis (EPPA) model, which is a recursive dynamic computable general equilibrium economic model that solves for prices that balance supply and demand over a 5-year period (Paltsev et al. 2015). In other words, economic actors optimize their welfare with perfect knowledge of the past, and no knowledge of the future. The costs are presented as a reduction in GDP from the reference scenario in the relevant year: 2050 or 2100 (provided in Appendix G: Projection Dataset). The costs represent economy-wide impacts of policy implementation. The economic model itself is not affected by the health and economic impacts of the resulting climate co-benefit, though this feedback would likely be small compared to the policy cost (Saari et al. 2015).

First, the more conservative estimate of policy cost offset is presented in Figure 24. This estimate is calculated with Krewski et al. (2009) as the $PM_{2.5}$ health impact function with an income elasticity of 0.4. While the annual policy cost ranges between 11% and 28% of annual GDP of Canada across policies and years of interest, the means of the air quality-related health co-benefits range between 0.1% and 0.3% of annual GDP. This result shows that 1 to 1.5% of the cost of climate policy is offset by the health benefits in Canada in the most conservative scenario. Another takeaway from the visualization is the diminishing returns for the more stringent P37 when the air quality-related health benefits are considered. The data for P37 show slightly higher benefits for both 2050 and 2100 at a much higher cost, while its 95% confidence interval is wider, showing the potential for greater benefits.

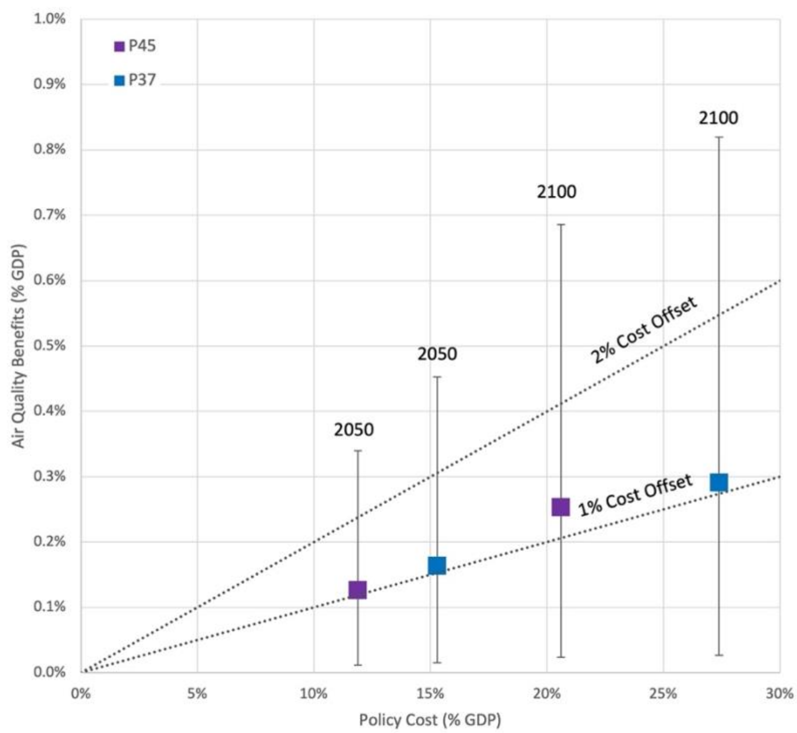


Figure 24. Cost of Climate Policy and Value of Mortality-Related Benefits from Reduced Climate Penalties on Ground-Level Ozone and Fine Particulate Matter. These values using Krewski et al. (2009) and Zanobetti et al. (2008) are expressed as fractions of Reference scenario Canadian GDP of the same year, using income elasticity of 0.4. Dashed lines indicate the percentage of climate policy costs offset by health benefits.

Next studied is the more optimistic estimate with Lepeule et al. (2012) as the $PM_{2.5}$ health impact function, with the income elasticity of 1. The annual policy costs are the same, between 11% and 28%, but the means of the air quality benefits range between 0.4% and 1.4%. In this optimistic case, the cost offset can be up to 3% for mid-century and 6% for end-of century, eclipsing the previous results from conservative estimates. However, the case of diminishing returns for policy stringency is further observed through this visualization as little increase in benefits are seen for P37 with larger increase in costs compared to P45.

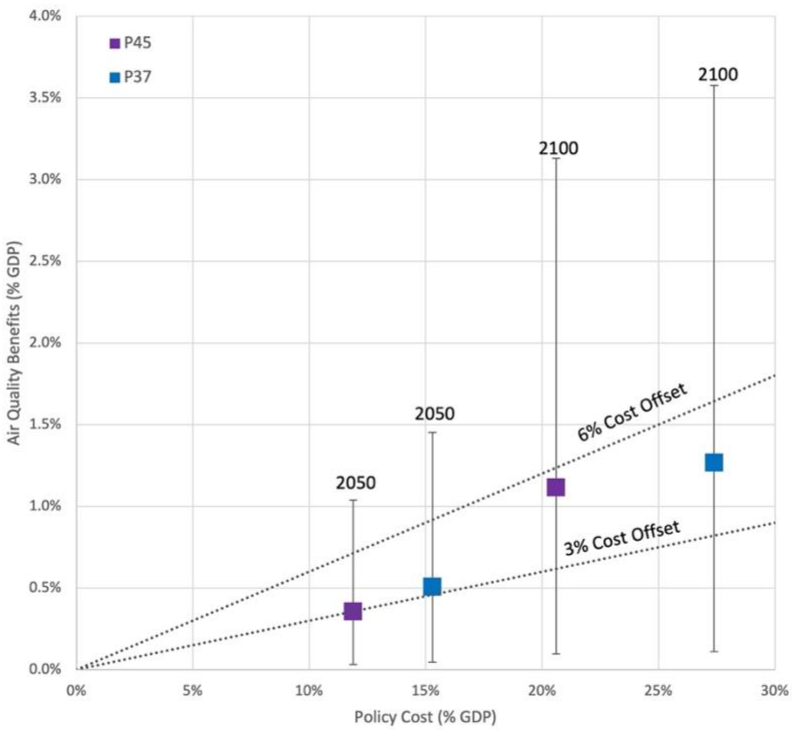


Figure 25. Cost of Climate Policy and Value of Mortality-Related Benefits from Reduced Climate Penalties on Ground-Level Ozone and Fine Particulate Matter. These values using Lepeule et al. (2012) and Zanobetti et al. (2008) are expressed as fractions of Reference scenario Canadian GDP of the year, using income elasticity of 1. Dashed lines indicate the percentage of climate policy costs offset by health benefits.

The policy cost and benefit results of Canada can be compared against the United States, retrieved from Saari et al. (2019). These values include morbidity as well as mortality, however the majority of the benefits are based on mortality, allowing direct comparison against the higher estimate case with Lepeule et al. (2012) as the $PM_{2.5}$ health impact function and income elasticity of 1 (Saari et al. 2019). As shown on Figure 26, the results for the United States display relatively similar benefits ranging from 0.5% to 2% of annual GDP but differ greatly on the cost of policy which are all below 15%, regardless of the policy or year. Note that Canada's costs are all above 15% apart from P45 in 2050. This demonstrates the relatively higher carbon-intensity of the Canadian economy and its dependence on industries such as oil-and-gas which is a sector with the most exported product from Canada for 2020 (OEC World 2020). This comparison is visualized in Appendix E: Canadian Export by Product Sector for Canada's exports and Appendix F: U.S. Export by Product Sector for U.S. exports, by the sector of their products. Despite a relatively clean electricity system, Canada's role as a major energy producer make its economy more energy intensive than other countries like the U.S. (Rivers 2010).

When considering the small fraction of costs offset, it is important to recall that these co-benefits relate only to the improvement of air quality due to the reduction of greenhouse gas emissions in Canada. They do not include numerous significant positive policy impacts of mitigating climate change. Regardless of how small Canada's potential for cost offset appears against the potential for the United States, it does not change the fact that there are great benefits in improving the air quality and reducing premature deaths in Canada.

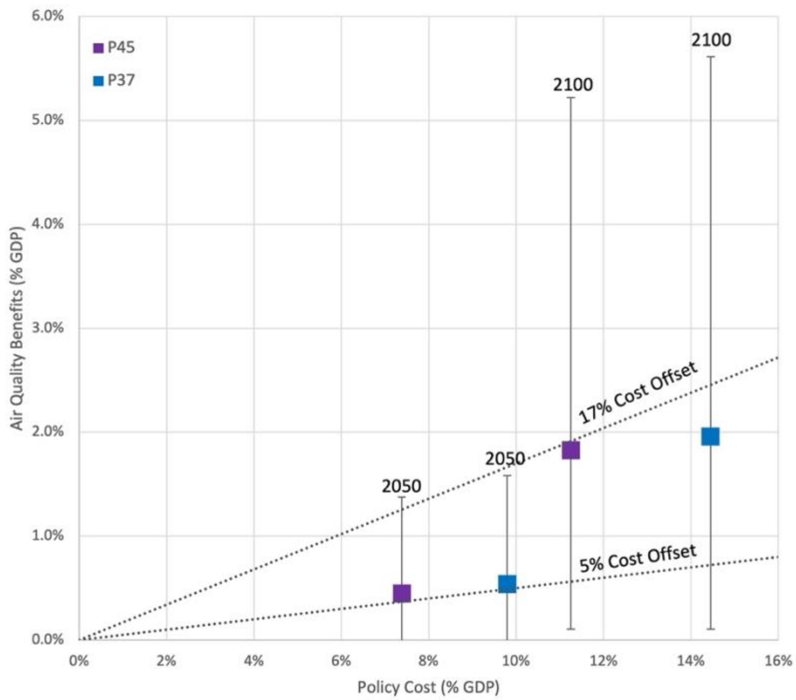


Figure 26. United States Cost of Climate Policy and Value of Mortality-Related Benefits from Reduced Climate Penalties on Ground-Level Ozone and Fine Particulate Matter from Saari et al. (2019). These values using Zanobetti et al. (2008) and Lepeule et al. (2012). are expressed as fractions of Reference scenario U.S. GDP of the same year, using income elasticity of 1. Dashed lines indicate the percentage of climate policy costs offset by health benefits.

5. Conclusions and Implications

This study brought insights to the impact on air quality and human health by climate policies through the quantification of the climate penalty and comparison with two different policy scenarios. Fine particulate matter and ground-level ozone were two pollutants in the scope, and they were analyzed using metrics of concentration, excess premature mortality, economic co-benefits, and policy cost offset. Data sources included NAPS (2000), the Canadian census (2001), IGSM-CAM-Chem framework including the CAM-Chem air quality model (2000, 2050, and 2100), outputs of which were processed and input to a new Canadian version of BenMAP-CE (BenMAP-Canada) to analyze the climate penalty and policy impact for three scenarios (REF, P45, P37) and three years (2000, 2050, and 2100). The modelled pollutant concentrations were validated against NAPS monitoring station-based concentrations with relative errors within acceptable bounds when compared with previous studies.

The climate penalty analysis found the national population-weighted average of the mean concentration of fine particulate matter to have an increase of 0.52 $\mu g/m^3$ in mid-century and 1.3 $\mu g/m^3$ at the end of century, while the mean ozone concentration was found to decrease by 0.67 ppb and 0.78 ppb in 2050 and 2100, respectively. Most of the increase in fine particulate matter was concentrated in urban areas along the southern border, such as Toronto, Montreal, Vancouver, and Calgary, while northern Canada and prairies experienced little change or a slight decrease in concentration. On the other hand, for the 21st century, nearly all areas of Canada experienced a decrease in ground-level ozone concentration, with the exception of the Greater Toronto Area. The health impact of the increase in fine particulate matter is estimated to eclipse that of ozone as the net increase in annual air quality-related premature mortality is expected to increase by between 1,100 (630, 1,600) and 2,800 (1,200, 4,400) in mid-century and 2,500 (1,500, 3,500) and 6,200 (2,900, 9,500) by the end of century. By 2100, this has the potential to nearly double the current annual $PM_{2.5}$-related mortality (Howard, Rose, and Rivers 2018). Economic damages associated with this premature mortality can be estimated using the VSL, providing a range between the lower projection with income elasticity of 0.4, to the higher projection with income elasticity of 1.0. Using Krewski et al. (2009) as the $PM_{2.5}$ health impact function, results in an additional loss of 16 (1.5, 44) to 21 (2.0, 5.8) billion dollars (CAD 2021) in 2050, and of 45 (4.3, 120) to 90 (8.5, 250) billion dollars in 2100. Using Lepeule et al. (2012) as the $PM_{2.5}$ health impact function, results in higher estimates with an additional loss of 42 (3.7, 120) to 55 (4.9, 160) billion dollars (CAD 2021) in 2050, and of 110 (10, 330) to 220 (20, 620) billion dollars in 2100.

The policy impact quantified the national population-weighted average of the mean concentration of fine particulate matter to decrease by 0.25 $\mu g/m^3$ in mid-century, and by 0.81 $\mu g/m^3$ and 0.97 $\mu g/m^3$ by 2100, for P45 and P37, respectively. Ozone, on the other hand, experienced an increase between 0.15 ppb and 0.27 ppb for 2050, and between 0.01 ppb and 0.58 ppb for 2100, depending on the policy implemented. The policy was most impactful in areas affected heavily by the climate penalty, particularly in major urban areas. Under climate policy, fine particulate matter is expected to decrease compared to the reference case in most of southern Canada, including the areas around Toronto, Vancouver, Calgary, and Montreal, while northern Canada and some of the prairies experience a slight increase. Ground-level ozone, on the other hand, increased in most of Canada with the exception of the Greater Toronto Area for the century. Decreases in annual premature mortality associated with fine particulate matter heavily outweighed the increases in mortality due to ozone, which resulted in a net decrease in annual premature mortality between 590 (370, 810) and 1,500 (690, 2,200) for mid-century, and between 1,800 (1,200, 2,300) and 4,800 (2,200, 7,000) for end-of-century, using the American Cancer Society Study and the Harvard Six Cities Study as the $PM_{2.5}$ health impact function, respectively. Using the VSL, this translated to a gain (or potential avoided loss) of a range between the projection with income elasticity of 0.4 to the projection with income elasticity of 1.0. Using Krewski et al. (2009) as the $PM_{2.5}$ health impact function, results in a gain of 8.3 (0.78, 22) to 11 (1.0, 30) billion dollars (CAD 2021) in 2050, and of 32 (3.0, 87) to 66 (6.2, 180) billion dollars in 2100. Using Lepeule et al. (2012) as the $PM_{2.5}$ health impact function, results in higher estimates with a gain of 22 (1.9, 62) to 28 (2.5, 80) billion dollars (CAD 2021) in

2050, and of 79 (7.0, 220) to 160 (14, 160) billion dollars in 2100. These co-benefits had the potential to offset 1% to 6% of the policy costs in Canada, which was much smaller than the potential offset of 5% to 17% of the United States. This was largely due to the higher policy cost in Canada where more of the economy is carbon-intensive (OEC World 2020; Rivers 2010).

5.1 Limitations

5.1.1 Air Pollutants in Scope

While fine particulate matter and ground-level ozone are air pollutants with serious health implications, there are more air pollutants relating to air quality and its health impact. The two pollutants in the study are responsible for the most widespread violations of the U.S. NAAQS, but the inclusion of other air pollutants would provide a clearer, and more complete picture of the trends of air pollution and its health impacts (Fiore, Naik, and Leibensperger 2015). In particular, NO_2 is included in Canada's Air Quality Health Index and is considered in Canada to have impacts on mortality risk. Future work could include this pollutant with the available concentration fields, contingent on validation and the insertion of the appropriate health impact functions into BenMAP-Canada.

5.1.2 Climate Penalty Processes Excluded

Model and data limitations meant that some processes by which climate change can affect air pollutant concentrations were not included in this analysis. A detailed discussion is provided in Garcia-Menendez et al. (2015). For the Canadian case, it is worth highlighting that wildfire emissions were held constant. This is significant as wildfires are the largest source of $PM_{2.5}$ in Canada (Meng et al. 2019). The impacts of climate change on wildfires will be complex, depending on changes in land use and precipitation, among other factors. One recent study suggests that climate change will increase the potential for unmanageable fires across Canada's forests, especially in northern and eastern boreal forests (Wotton, Flannigan, and Marshall 2017).

5.1.3 Gaps in Data Collection

The best available data were used for the study, but there were limitations to availability. For the beginning of century data, the model compiled data from 1981 to 2010, rather than 1986 to 2015 (which centres around the year 2000) due to the availability of the data. Furthermore, the availability for NAPS station data were limited, biasing the validation data towards more recent years. This was especially true for fine particulate matter which had daily 24-hour mean data only beginning with 1995.

The census data for 2001 was used instead of 2000 as the census data was deemed to be more accurate and reliable than the projected data for 2000, which would be based off the last census date. This choice, again, is not expected to degrade the results meaningfully but is a limitation to the study.

Mortality data at the CD-level are unavailable in the census, as it is considered to be sensitive. Provincial mortality data were used to estimate the baseline CD-level mortality for BenMAP. Finer resolution mortality data would improve the accuracy of the mortality estimates.

5.1.4 Data Validation

The modelled air pollutant concentrations were validated against observed concentrations from monitoring stations from the NAPS data portal. While the performance of the population-weighted averages was deemed sufficient with respect to literature, the relative error in values were 47% and 66% for $PM_{2.5}$ and ground-level ozone, respectively (Lamarque et al. 2012; Kelly, Makar, and Plummer 2012). These error values are not small to start with, and certainly have room for improvement through increased accuracy in the MIT IGSM-CAM-Chem framework's inputs and structure. Nonetheless, these errors in concentration are dwarfed by the uncertainty in the health and economic responses, which contribute relative errors of 90% below the mean, and 180% above the mean.

Another significant limitation in validation was in the NAPS data availability. NAPS has many stations across the nation, but they tend to be only in areas of interest, usually in populated areas. While this may be sufficient for our study as it is mainly interested in the health impact or mortality, this dataset may omit the rural population with no nearby monitoring stations to provide data to the NAPS program. Furthermore, the number of stations providing measurements for our validation changed dramatically throughout the period included in baseline concentration calculations. There were significantly more stations being considered in the latter half of the 30-year period around 2000, as the first measurements for $PM_{2.5}$ begins only in 1995 with one station. This led to the sampling of the pollutants much closer to the later years, especially with $PM_{2.5}$, creating a temporal bias in the data used to validate the modelled data.

While population-weighted averages are commonly used in air quality and health impact studies as they relate to humans, it is limited that one national average is compared with another. This limits the ability to locate areas of improvement, as they are compiled and averaged.

5.1.5 Grid size

The relatively coarse grid size of 2.5° by 1.89° is another limitation of the CAM-Chem model outputs for the purposes of health impact assessment. For some analyses, this grid size was too large to speak for a specific location or city but was deemed sufficient for understanding long-term trends in air quality in Canada and studying the more general urban areas.

The limitation of this study is that the resolution is not fine enough to look at the cities in more detail, as the grid cell size was predetermined for previous global large ensemble simulations (Garcia-Menendez et al. 2015). While the current method with population-weighted averaging is sufficient for understanding nation-wide trends for the purpose of the study, finer resolution would provide us with a better understanding of local changes and increase the accuracy of mortality estimates. It is quite possible that the ozone concentrations in the urban areas are much worse than it currently shows but the effects are dampened due to the surrounding areas with lower levels of pollution. The effect of model resolution on concentrations has been studied extensively, though the effects are often small compared to uncertainty associated with health responses (Thompson, Saari, and Selin 2014). Future studies with finer resolution concentrations, demographics, and baseline health data could better inform these urban-scale questions. Nevertheless, with the current setup, the national trends for both pollutants can be seen and converted to mortality for further understanding of their impact.

5.1.6 Uncertainty in BenMAP Output

The Monte-Carlo simulations performed on BenMAP resulted in distributions. The 95% confidence intervals are included when presenting the data, in parentheses. These confidence intervals are often large, especially for valuation. For mortality, the range is between 30% to 50% of the mean, while the valuation ranges between 90% and 190% of the mean, dwarfing the errors in the concentration and the mortality estimation (Appendix H: 95% Confidence Interval Relative Error). While the upper and lower error values align with U.S. values, the error ranges are wide and are areas of improvement for future research on the health and economic responses to air pollution. Due to the range of the error and the asymmetrical distribution, some BenMAP runs were redone when they had opposite distributions (with the longer tail of ozone outweighing the short tail of particulate matter) to avoid statistical insignificance when taking the summation of the confidence intervals to compile the mortality and valuation for both pollutants. BenMAP expects data to be input such that the baseline is the more polluted scenario, and the control is the less polluted. After a preliminary run to determine whether the concentration decreases or increases, the scenarios were rerun to comply with BenMAP's input expectation. These are limitations in the software used, as well as the health functions for the pollutants, which can be improved.

5.1.7 Cost Offset Calculation

This study presents the percentage of the policy cost offset in a given year by air quality co-benefits. Ideally, instead, the net present value of co-benefits minus costs would be calculated. However, this calculation would require the full annual profiles of both costs and co-benefits for all years in which the policy is expected to have meaningful impacts. This is infeasible due to modelling and computational limitations. Computational limitations include the time required to assess air pollutant concentrations and their attendant impacts across at least a century. Modelling limitations include the fact that the economic model provides cost estimates on a 5-year period. Thus, the comparison to annual cost is intended to provide a reference for the significance of the co-benefits (Saari et al. 2019).

5.2 Policy Implications

The findings of this study are relevant to policymakers concerned with the effect of climate change on mortality and the costs. The air quality-related mortality is expected to increase in the next century, as much as doubling the mortality rate of 2015 by the end of century if we continue business-as-usual. Most of the health risks are concentrated in population-dense areas such as the urban centres of Toronto, Montreal, and Vancouver. These potential risks are not entirely avoidable in the policy scenarios modelled but the risk is shown to greatly decrease with policy implementation. Policies have the potential to reduce the increase in mortality such that avoided annual mortality at the end of century is up to 5,000 less than the reference scenario. The policies display diminishing returns with more stringency in terms of avoided mortality. When compared with P45, the increase in policy cost for P37 outweigh the additional health co-benefits gained by the policy. The shares that carbon-based products occupy in the Canadian economy, and the extent of existing decarbonisation in the electricity sector, lead to larger policy costs and lower cost offset by the health benefit, when compared with the United States. As a result, between 1% to 6% of the cost of policy is estimated to be offset by the air quality-related health benefits in VSL. These co-benefits serve to effectively decrease the cost of climate policy and should be included in full cost-benefit analyses of climate policy.

5.3 Future Work

This study provides an initial understanding of the health impact in Canada due to changes in air pollution from implementing climate policies. There are many branches that can be studied with this work as a foundation.

One is in studying the uncertainty in the results to have more accurate understandings of the various scenarios. As mentioned above, the uncertainties in the BenMAP output are wide and are a great opportunity for improvement in the results.

Another area of study is comparing the results with Canada's Air Quality Benefits Assessment Tool (AQBAT). While BenMAP is a U.S. EPA-based software that can be used for other regions, AQBAT is developed by Health Canada to estimate health impacts of changes in air quality in Canada. Unfortunately, there were compatibility issues and errors to progress this path in the research plan, but this would provide another perspective with which to compare the results.

Lastly, higher resolution modelling with smaller grid sizes would provide a much more detailed understanding of trends. The insights can be much more specific to a city or a municipality, rather than a broad general area as it is in this study. This will be possible as such data becomes available. The results of this work can inform more detailed high-resolution studies in the specific areas of concerned identified herein.

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Appendix A: Climate Penalty Mortality

Table 19. Unprojected Change in Mortality due to Climate Penalty for Each Study. 95% confidence interval displayed in parentheses, rounded to two significant figures.

Scenario	Year	Ozone	$PM_{2.5}$ (ACS)	$PM_{2.5}$ (Six City)
REF	2000 - 2050	-82 (-120, -44)	640 (440, 850)	1,500 (740, 2,200)
	2000 - 2100	-96 (-140, -52)	1,600 (1,100, 2,100)	3,700 (1,900, 5,600)

Appendix B: Climate Penalty Valuation

Table 20. Unprojected Change in Valuation due to Climate Penalty for Each Study. 95% confidence interval displayed in parentheses, rounded to two significant figures. Currency is in billions of USD (2000).

Scenario	Year	Ozone	$PM_{2.5}$ (ACS)	$PM_{2.5}$ (Six City)
REF	2000 - 2050	-0.60 (-1.7, -0.054)	4.2 (0.39, 11)	9.6 (0.86, 27)
	2000 - 2100	-0.51 (-1.5, -0.046)	10 (0.95, 28)	23 (2.1, 67)

Appendix C: Policy Impact Mortality

Table 21. Unprojected Change in Mortality due to Policy Impact for Each Study. 95% confidence interval displayed in parentheses, rounded to two significant figures.

Scenario	Year	Ozone	$PM_{2.5}$ (ACS)	$PM_{2.5}$ (Six City)
REF vs. P45	2050	20 (11, 29)	-310 (-410, -210)	-720 (-1,100, -360)
	2100	6.7 (3.9, 9.0)	-1,000 (-1,300, -690)	-2,300 (-3,500, -1,200)
REF vs. P37	2050	33 (18, 49)	-320 (-420, -220)	-740 (-1,100, -370)
	2100	74 (40, 110)	-1,200 (-1,600, -820)	-2,800 (-4,200, -1,400)

Appendix D: Policy Impact Valuation

Table 22. Unprojected Change in Valuation due to Policy Impact for Each Study. 95% confidence interval displayed in parentheses, rounded to two significant figures. Currency is in billions of USD (2000).

Scenario	Year	Ozone	$PM_{2.5}$ (ACS)	$PM_{2.5}$ (Six City)
REF vs. P45	2050	0.12 (0.011, 0.35)	-2.0 (-5.3, -0.18)	-4.5 (-13, -0.40)
	2100	0.042 (0.0039, 0.12)	-6.6 (-18, -0.61)	-15 (-43, -1.4)
REF vs. P37	2050	0.21 (0.019, 0.59)	-2.0 (-5.5, -0.19)	-4.6 (-13, -0.41)
	2100	0.48 (0.043, 1.4)	-7.6 (-21, -0.71)	-18 (-43, -1.4)

Appendix E: Canadian Export by Product Sector

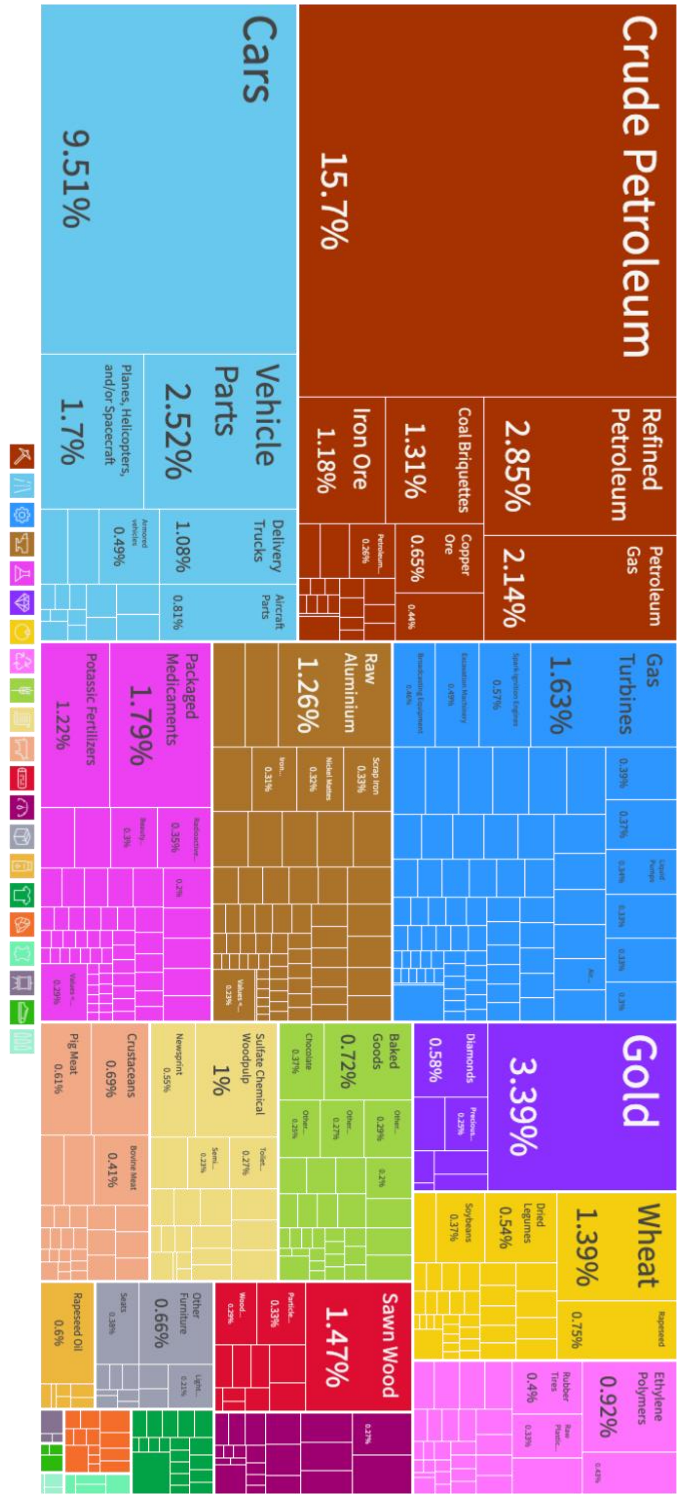

Figure 27.Canada Export Shares by Trade Value in 2019 [OEC World 2020]. Products of the oil and gas sector are shown to be around 20% of all exports from Canada, supporting the dependence on carbon-intensive products. Of the total export value of $430 billion USD, crude petroleum is the top export at 16% or $68 billion USD.

Appendix F: U.S. Export by Product Sector

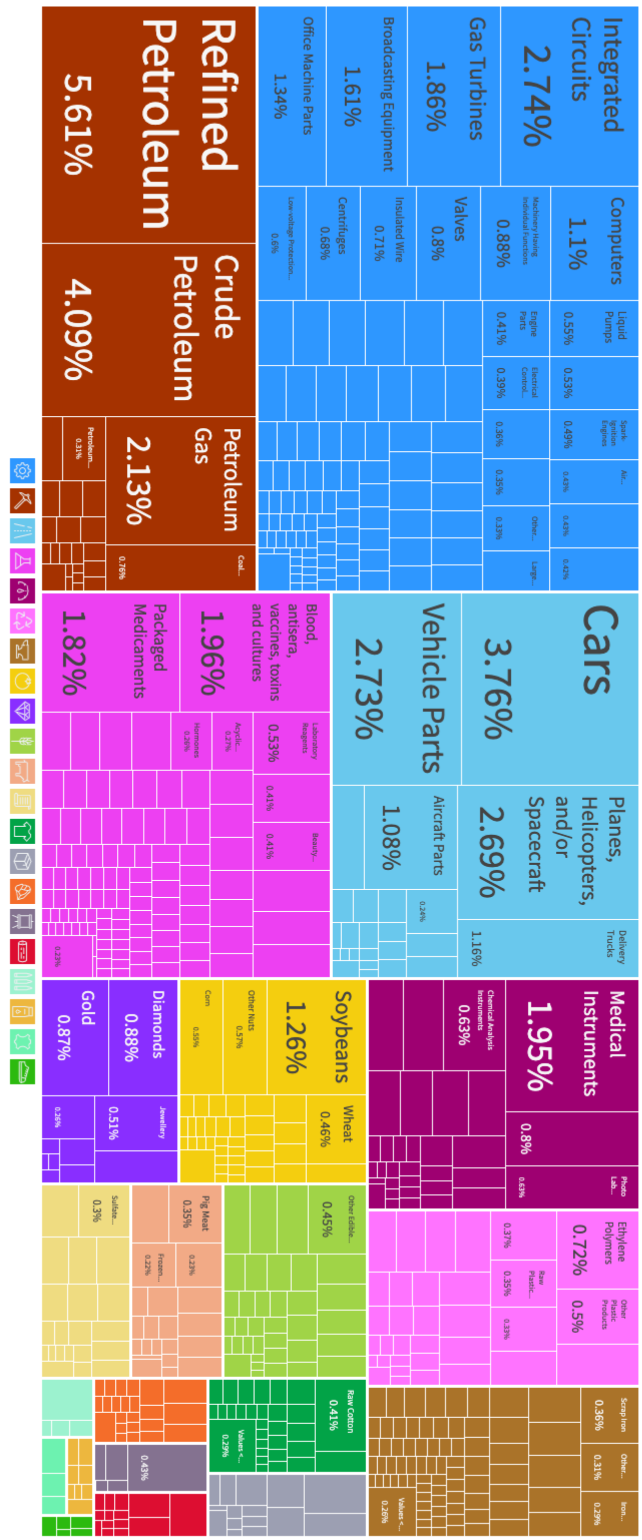

Figure 28. U.S. Export Shares by Trade Value in 2019 [OEC World 2020]. The shares of products of the oil and gas sector are less to be around 12% of all exports from the US, supporting the lower dependence on carbon-intensive products. Machine products are the highest exports, followed by mineral products such as oil and gas.

Appendix G: Projection Dataset

Table 23. Additional Projection-Related Data and Sources.

Description	Year	Value	Source
Canada REF vs. P45 GDP Ratio	2050	0.119	Paltsev et al. 2015
Canada REF vs. P45 GDP Ratio	2100	0.206	Paltsev et al. 2015
Canada REF vs. P37 GDP Ratio	2050	0.153	Paltsev et al. 2015
Canada REF vs. P37 GDP Ratio	2100	0.274	Paltsev et al. 2015
US REF vs. P45 GDP Ratio	2050	0.074	Paltsev et al. 2015
US REF vs. P45 GDP Ratio	2100	0.113	Paltsev et al. 2015
US REF vs. P37 GDP Ratio	2050	0.098	Paltsev et al. 2015
US REF vs. P37 GDP Ratio	2100	0.145	Paltsev et al. 2015

Appendix H: 95% Confidence Interval Relative Error

Table 24. 95% Confidence Interval Relative Error from the Mean, for Mortality and Valuation. The 95% confidence interval ranges for mortality average around ± 42%, while the averages of all valuation 95% confidence intervals range from -90% to +180% of the mean.

Metric	Scenario	Author	2.5 percentile	97.5 percentile
Mortality	REF 2000 REF 2050	Krewski et al. 2009	-32%	31%
Mortality	REF 2000 REF 2100	Krewski et al. 2009	-32%	32%
Mortality	REF 2000 REF 2050	Zanobetti et al. 2008	-47%	45%
Mortality	REF 2000 REF 2100	Zanobetti et al. 2008	-45%	45%
Mortality	REF 2000 REF 2050	Lepeule et al. 2012	-50%	50%
Mortality	REF 2000 REF 2100	Lepeule et al. 2012	-49%	49%
Valuation	REF 2000 REF 2050	Krewski et al. 2009	-91%	173%
Valuation	REF 2000 REF 2100	Krewski et al. 2009	-91%	173%
Valuation	REF 2000 REF 2050	Zanobetti et al. 2008	-91%	184%
Valuation	REF 2000 REF 2100	Zanobetti et al. 2008	-91%	184%
Valuation	REF 2000 REF 2050	Lepeule et al. 2012	-91%	184%
Valuation	REF 2000 REF 2100	Lepeule et al. 2012	-91%	184%
Mortality	REF 2050 P37 2050	Krewski et al. 2009	-32%	32%
Mortality	REF 2050 P45 2050	Krewski et al. 2009	-32%	32%
Mortality	REF 2100 P37 2100	Krewski et al. 2009	-32%	32%
Mortality	REF 2100 P45 2100	Krewski et al. 2009	-32%	32%
Valuation	REF 2050 P37 2050	Krewski et al. 2009	-91%	173%
Valuation	REF 2050 P45 2050	Krewski et al. 2009	-91%	173%
Valuation	REF 2100 P37 2100	Krewski et al. 2009	-91%	173%
Valuation	REF 2100 P45 2100	Krewski et al. 2009	-91%	173%
Mortality	P37 2050 REF 2050	Zanobetti et al. 2008	-46%	46%
Mortality	P37 2100 REF 2100	Zanobetti et al. 2008	-46%	45%
Mortality	P45 2050 REF 2050	Zanobetti et al. 2008	-46%	46%
Mortality	P45 2100 REF 2100	Zanobetti et al. 2008	-42%	36%
Valuation	P37 2050 REF 2050	Zanobetti et al. 2008	-91%	184%
Valuation	P37 2100 REF 2100	Zanobetti et al. 2008	-91%	184%
Valuation	P45 2050 REF 2050	Zanobetti et al. 2008	-91%	184%
Valuation	P45 2100 REF 2100	Zanobetti et al. 2008	-91%	177%
Mortality	REF 2050 P37 2050	Lepeule et al. 2012	-50%	50%
Mortality	REF 2050 P45 2050	Lepeule et al. 2012	-50%	50%
Mortality	REF 2100 P37 2100	Lepeule et al. 2012	-50%	49%

Mortality	REF 2100 P45 2100	Lepeule et al. 2012	-50%	49%
Valuation	REF 2050 P37 2050	Lepeule et al. 2012	-91%	185%
Valuation	REF 2050 P45 2050	Lepeule et al. 2012	-91%	185%
Valuation	REF 2100 P37 2100	Lepeule et al. 2012	-91%	185%
Valuation	REF 2100 P45 2100	Lepeule et al. 2012	-91%	185%