Political Governance, Socioeconomics, and Weather Influence Greenhouse Gas Emissions across Subnational Jurisdictions in Canada

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Conservation Biology

Department of Renewable Resources

University of Alberta

Abstract

The drastic and immediate reduction of global greenhouse gases (GHG) is vital if humanity is to avoid the moderate to severe effects of a changing climate. To successfully lower these emissions, it is necessary to integrate and harmonize GHG reduction policies across horizontal and vertical political jurisdictions. There has been much worthwhile research conducted across national and international jurisdictions but uncertainty about integrating emission reduction policies across subnational jurisdictions persists. Quantifying the drivers of emission variation across these subnational jurisdictions is a necessity in developing effective future emission reduction policies. This thesis contributes insights into the much needed and growing body of subnational emission policy integration research by presenting several studies that quantify the effects of political governance, socioeconomics, and weather drivers on GHG emissions across subnational jurisdictions in Canada.

I begin by quantifying the effects of political governance, socioeconomics, and weather on provincial per-capita GHG emissions across Canada from 1990 to 2019. My regression models explained 75.3% to 98.8% of the variation in GHG emissions across the ten Canadian provinces. Socioeconomics was correlated with most of the emission variation (46.1%), then weather (1.4%). Political governance followed lastly (0.7%) but had a strong interaction with socioeconomic factors. Of all factors tested, energy use efficiency affected GHGs the most, being associated with lower emissions in eight provinces. I conclude that socioeconomic factors are the strongest drivers of provincial GHG emissions, while political governance alone has a limited ability to compel changes in emission variation if the regional economy is not considered. Furthermore, investment in the dispersion of energy efficient technologies should have the highest return in reducing emissions.

I then explored how the drivers of emissions change across vertical subnational jurisdictions, from the city to the provincial jurisdictions, by modelling the effects of political governance, household socioeconomics, and weather drivers on household GHG emissions from electricity, natural gas, and petrol for Canadian province and city jurisdictions from 1997-2009. My regression models explained 60.6% to 98.3% of GHG variation for cities and 71.1% to 99.3% for provinces. Variation partitioning showed that emission variation attributed to household socioeconomics, the most selected variable category, varied from 15.6% to 49.0% for cities and 66.6% to 75.2% for provinces. Political governance was associated with at most 4.8% of emission variation and was only significant for city jurisdictions. However, it did have joint contributions with other variable categories, especially socioeconomics (47.6% for electricity from non-fossil fuels). I conclude that it is crucial to integrate locally based, energy source specific policies into larger subnational and national based strategies to limit household emissions.

In the last data chapter, I use quantile regression to quantify the nuanced effects of demographic, socioeconomic, and household factors on consumption-based community CO_2 emissions for 1679 communities across Canada in 2015. The findings show that population then affluence were the most significant variables affecting total community emission variation, whereas affluence affected per capita community emission most of all factors. However, the effects of these factors on emissions were not uniform across quantiles. The effect sizes decreased for population and increased for affluence from lower to higher community emission quantiles. Additionally, poverty was correlated with higher emissions for all quantiles across Canada. I conclude that effective emission reduction policies must be based on the characteristics of individual communities, especially considering the variation in population and affluence across communities. Furthermore, poverty alleviation may effectively lower CO_2 emissions and should be considered in future climate mitigation and adaptation policies.

Overall, the findings of my thesis provide insights that are useful for the development of future emission reduction policies by quantifying the effects of political governance, socioeconomic, and weather factors on GHG variation. This thesis also explores how the drivers of emissions change across vertical and horizontal subnational jurisdictions, a much-needed contribution to better integrate subnational emission reduction actions with national and international climate change strategies.

Preface

This is an original work by Scott Boyce.

Chapter Two was conceived by Scott Boyce under the guidance of Fangliang He with insights provided by Debra Davidson and Vic Adamowicz. Scott Boyce compiled and analyzed the data. Scott Boyce wrote the manuscript with revisions from Fangliang He. Chapter 2 has been published as:

Boyce, S., & He, F. (2022). Political governance, socioeconomics, and weather influence provincial GHG emissions in Canada. *Energy Policy*, *168*, 113019. https://doi.org/10.1016/j.enpol.2022.113019

Chapter Three was devised by Scott Boyce with inputs from Fangliang He. Scott Boyce compiled and analyzed the data. The chapter was written by Scott Boyce with revisions from Fangliang He.

Chapter Four was created by Scott Boyce with the guidance of Fangliang He. Scott Boyce compiled and analyzed the data. The chapter was written by Scott Boyce with revisions from Fangliang He.

All data used in this thesis was obtained from publicly available sources.

Acknowledgements

I show my deepest gratitude to my supervisor Professor Fangliang He for his support, sharing of expertise, and patience as I developed my researcher skillset over the years. It has been an honour and privilege to have worked with Professor He throughout my graduate program. I also thank my supervisory committee members Professors Debra Davidson and Vic Adamowicz for the advice, inspiration, and, at times, hard yet insightful criticisms which helped me hone my critical thinking and researcher skillsets. Additionally, Professors John Parkins, Jean Crête, and Carol Frost all have my thanks for being candidacy and defense examiners.

Thank you to all my past and present lab colleagues at the Biodiversity & Landscape Modeling Lab. I owe special thanks to Dingliang Xing, who was there to provide statistical guidance early in my graduate program; David Deane, who continues to share many life experiences with me, both professional and personal; Pembe Nozohourmehrabad, for the ongoing friendship and support; and Kun Xu, for sharing insights about research and life alike.

I thank many public organizations for providing access to data. This includes Statistics Canada, Natural Resources Canada, Environment and Climate Change Canada, the many collaborators who made the Global Gridded Model of Carbon Footprints easily available to the public, and the many provincial and municipal governments who kindly gave me access to the voting records, Hansards and city council minutes used in my research.

Lastly, I give my greatest of thanks to my amazing family and friends who have been there for me, not only for the writing of this thesis, but through the good and bad times of a life well lived. You have graciously shared your time and resources with me over the years when I needed it the most, asking for nothing in return except that I continue to follow my dreams and passions. I would not be where I am today without you and for that I am eternally indebted to each of you.

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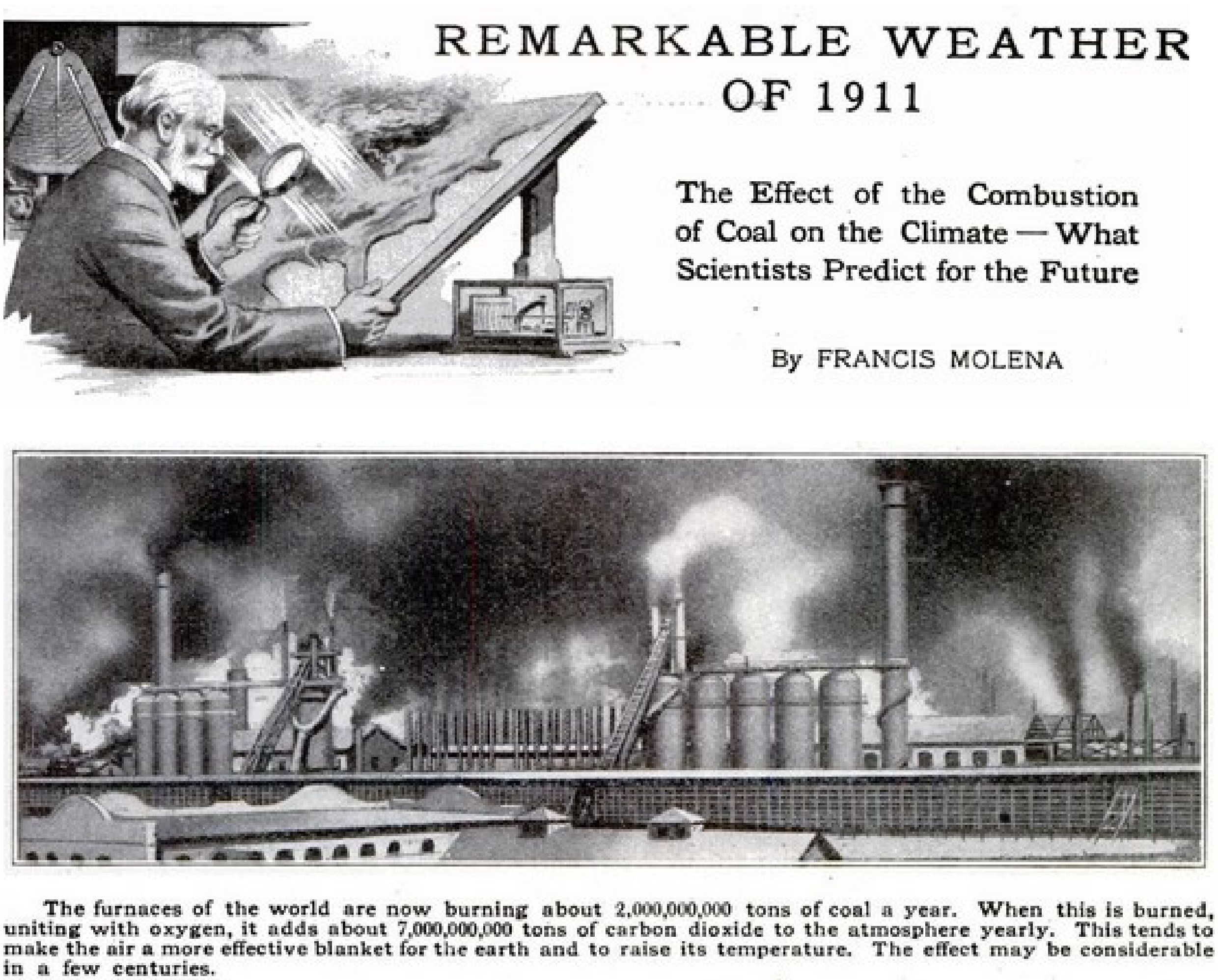
Chapter One: Introduction

1.1 Context and snapshot of research

Understanding the drivers of anthropogenic greenhouse gas (GHG) emissions across different jurisdictions, from local communities to the national level, is critical for climate change mitigation policy decision making. However, the problem is not well understood, with much uncertainty about the sources of emissions. As an example, the role of governments to limit emissions in different jurisdictions has been highly publicized and debated but many of the debates lack quantitative results about the effect of political intervention on GHG emission variation. Furthermore, where quantified, research on how politics influence emission variation relative to other drivers of emissions such as economics, demographics, and weather remains scarce. In this thesis, I attempt to fill in this knowledge gap by quantifying the subnational political governance, socioeconomic, and weather-related drivers of GHG emissions across Canada. After reviewing the literature on the drivers of GHG emissions in Chapter 1, I present three data chapters that quantify and interpret the significance of the drivers of emission variation across horizontal and vertical jurisdictions, providing insights into future emission reduction policies. Chapter 5 concludes my thesis where I discuss the relevance, significances, and implications of my research in developing future GHG emission reduction policies. I also identify research gaps requiring further attention while discussing uncertainties and limitations in my own research.

1.2 A brief history of the debate on environmental change and GHG emissions

Debate and political division surrounding climate change may be a regular occurrence in modern environmental discourse, but the controversary that has led to this discourse can be traced back well over a century and half ago. Both Eunice Foote (1856) and John Tyndall (1861) were early discoverers of GHGs and their potential to warm the atmosphere. Shortly after that, Svante Arrhenius (1896) attempted to quantify the climate changing effect of carbon dioxide, stating that, at the time of his calculations, an increase in the concentration of CO_2 in the atmosphere by 2.5 to 3 times would cause temperatures in Arctic regions to rise 8 to 9°C. By 1912, the effects of burning fossil fuels on the climate had already moved into the mainstream media, being covered in an article in Popular Mechanics (Molena, 1912; Fig. 1.1).



REMARKABLE WEATHER OF 1911

The Effect of the Combustion of Coal on the Climate — What Scientists Predict for the Future

By FRANCIS MOLENA

The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

Figure 1.1 Headline and figure with caption from climate change article in the March edition of Popular Mechanics, 1912.

Post World War 2 was a time of renewed industrialization and economic growth, but it also allowed for a deeper understanding of global economic disparity and resource scarcity. In 1955, economist Simon Kuznets proposed that economic inequality was directly related to the developmental stage of a nation's economy, initially increasing inequality in the early economic development stages, plateauing for mid-development stages, and then decreasing as a nation enters the more advanced stages of economic development (Kuznets, 1955). This inverted 'U'-shaped pattern, termed the Kuznets curve, led to the formation of the much-debated environmental Kuznets curve (EKC; Fig. 1.2) by (Grossman & Krueger, 1991). Grossman and Krueger argued that air quality follows a Kuznets curve where air quality is poor during early economic development, plateaus for mid-development, and then increases in quality as an economy becomes more advanced. Overall, the viability of the EKC in relation to climate change research, and its potential to provide meaningful GHG reduction policy insights, is mixed (Dasgupta et al., 2002; Stern, 2004) and is still being debated (see Ota, 2017 for a contemporary example).

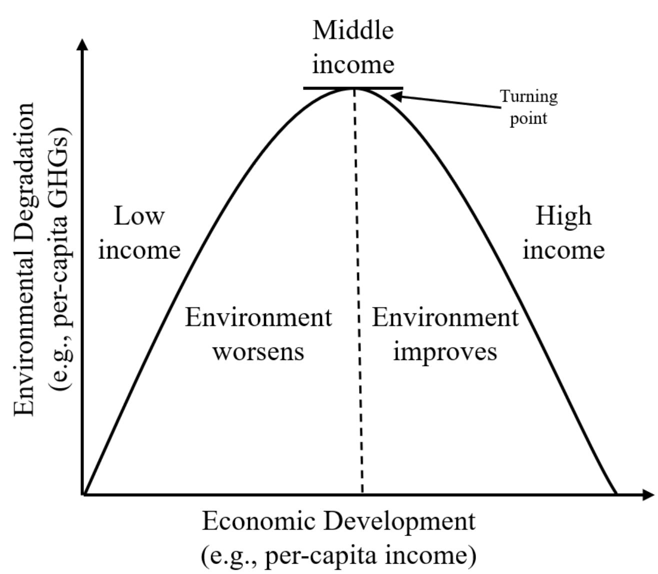


Figure 1.2 The environmental Kuznets curve.

The late 1960's and early 1970's saw debates focusing on environmental change and stewardship heat-up. The Population Bomb (Ehrlich, 1968) and The Limits to Growth (Meadows et al., 1972) initiated highly controversial stances about the effects of growing populations and affluence on the planet, essentially stating that unhindered population and economic growth would have dire global consequences, inhibiting the ability of the planet to support the needs of humanity. Around this time, Garret Hardin released his essay The Tragedy of the Commons (1968), arguing that, amongst several examples, in an unregulated waste management system it is more cost effective for individual polluters to haphazardly release pollution into the shared atmospheric and aquatic systems than to bear the costs to properly treat the waste. This concept has been revisited many times in climate change research (Dietz et al., 2003; Engel & Saleska, 2005; Ostrom et al., 1999; Wang & Chen, 2013), recognizing that the global atmosphere has been effectively utilized by polluters as a commons for releasing GHG emission waste, externalizing the costs to properly treat waste emissions. These costs are borne by, and to the detriment of, the health of society and the global biosphere.

Along with the recognition that specific polluters release contaminants into the environmental commons at the expense of the well-being of society, a better understanding of the societal drivers of environmental degradation became more openly discussed amongst researchers, policymakers, and citizens alike. A highly influential debate in the early 1970's between Barry Commoner, Paul Erhlich, and John Holdren about the effects that population, affluence, and technology have on the environment led not only to the formalization of the widely used I=PAT equation (*i.e.*, environmental impact = population × affluence × technology), but also initiated unprecedented increases in environmental regulations across the United States, including the establishment of the Environmental Policy Act, Clean Air Act, Clean Water Act, Toxic

Substance Control Act, Resource Conservation and Recovery Act, amongst many other legislations (Chertow, 2000). Furthermore, the I=PAT equation was a precursor to the Kaya identity (Kaya, 1990), a specialised version of the I=PAT equation that is commonly used to decompose the drivers of GHG emissions by the UN (IPCC, 2014) and researchers (see Raftery et al., 2017 for an example).

Another highly publicized debate, and wager, between Paul Erhlich and Julian Simon about resource scarcity and the ability of human ingenuity to address scarcity issues took place in the 1980's (Ehrlich, 1981; Simon, 1981). Ehrlich argued that resources are finite, becoming scarcer as they get used, while Simon argued that human ingenuity was able to address any concerns of resource scarcity. For the bet, Erhlich chose 5 metal commodities (*i.e.*, chromium, copper, nickel, tin, and tungsten) that he thought would become scarcer, leading to an increase in price, by September of 1990. If these commodities became cheaper, then Simon would win the bet. All commodity prices fell, making Simon the clear winner of the bet (Desrochers et al., 2021a), insinuating that human ingenuity and technological innovation was able to address many of the world's environmental concerns. The debate initiated in this bet is still being carried out by researchers (Desrochers et al., 2021a, 2021b; Pooley & Tupy, 2020).

Like the Erhlich-Simon wager, the debate between proponents of the treadmill of production and proponents of ecological modernization gained momentum in the 1990's. The treadmill of production viewpoint argues that economic growth inherently requires the continuous and expanding exploitation of natural resources to produce the goods and services required of a growing economy (Gould et al., 2004; Schnaiberg, 1980). This inevitably leads to increasing environmental degradation and the release of pollutants as the necessary resources required for production are extracted, regardless of the economic developmental stage of a given society.

Counter to this viewpoint, ecological modernization argues that economic growth spurs technological improvements and human ingenuity (Spaargaren & Mol, 1992). This includes the modernization of society's ecological understanding and the ability to mediate past environmental degradation through technological advancement, leading to a decoupling of environmental degradation and economic growth, a reflection of the EKC concept discussed above. Research that has tested both perspectives in relation to GHG emissions has provided varied results, showing that neither perspective is definitively correct, and that the topic requires additional and more nuanced considerations of the organization of production and the structure of international trade (Jorgenson & Clark, 2012).

The threat of climate change and the necessity to limit GHG emissions was increasingly recognized throughout the 1990's, becoming more heavily debated in and amongst nations across the globe. Following the sustainable development policy framework outlined in the Brundtland Report (World Commission on Environment and Development, 1987), the Earth Summit held in Rio de Janeiro, Brazil in 1992 introduced much of the world to growing global environmental concerns (Cardinale et al., 2012; Clapp & Helleiner, 2012). This included establishing the need to lower global GHGs (Hsu et al., 2013) and popularizing the concept of the precautionary principle (Ingram, 2002), while also overseeing the formation of the United Nations Framework Convention on Climate Change (UNFCC; UN, 2022). An extension of the UNFCCC, the Kyoto Protocol international treaty, was adopted in 1997 to commit industrialized nations and economies in transition alike to limit, then reduce their GHG emissions (UNFCCC, 2022). To date, the outcomes of the Kyoto Protocol are mixed, with some nations making serious efforts to limit emissions while others have done comparably little (Almer & Winkler, 2017; Atici, 2022; Kuriyama & Abe, 2018; Wang & Chen, 2013).

Since the early 2000's, debates on the drivers of anthropogenic GHGs, the extent these GHGs affect the global climate, and what we should do to address the existential threat of climate change continue to attract the attention of policymakers, researchers, industry, and the general populace. The controversial Stern Review on the Economics of Climate Change was released in 2006 where the author, Nicholas Stern, provided evidence that climate change "is the greatest and widest-ranging market failure ever seen" and offered a variety of potential market-based policy options to address this failure (Stern, 2006). In 2015, the UN Conference of Parties 21 (COP21) took place in Paris, France. This conference led to the Paris Agreement international treaty, a legally binding treaty in which each of the 196 signatory countries must submit and commit to their nationally determined contributions to reduce national GHGs (UNFCC, 2022). The International Panel on Climate Change (IPCC) began releasing assessment reports on climate change in 1990 (IPCC, 2022a), with the Sixth Assessment Report released in late 2021 and throughout 2022 (IPCC, 2022b). These reports are a comprehensive summation of our global understanding of climate change including what we must do to mitigate and adapt to a changing climate. In the Sixth Assessment Report, Working Group I's contribution titled 'The Physical Science Basis' (IPCC, 2021), it states that "it is unequivocal that human influence has warmed the atmosphere, ocean and land". Regardless of the sheer volume of evidence that science has collected over a century and half of research to justify such a claim, and the increasing frequency and intensity of climate related events adversely affecting people across the globe (Hoegh-Guldberg et al., 2019), there remains climate change denial, including organized counter movements by proponents of fossil fuel exploitation (Dunlap & McCright, 2011; Megura & Gunderson, 2022), in contemporary climate change discourse.

1.3 Decreasing emissions in a world of increasing consumption

The global community is currently consuming ecological goods and services at an annual rate equivalent to the regenerative capacity of approximately 1.75 Earths (Global Footprint Network, 2020). The historical procurement of resources to supply this consumption has led to an unprecedented release of GHG emissions since pre-industrial times (Joos & Spahni, 2008), with emission releases being most pronounced over the last several decades, more than any other time in recorded history (NOAA, 2019). This release of climate changing agents has caused the average global temperature to warm about 1.1ºC since 1850 (IPCC, 2021). The global average temperature must remain below a threshold of 1.5ºC above pre-industrial temperatures over the coming century to avoid the moderate to severe detrimental effects of this warming (Hoegh-Guldberg et al., 2019; IPCC, 2018). Without timely and efficient emission reduction intervention, this temperature increase is estimated to occur between 2030 and 2052 (Goodwin et al., 2018; IPCC, 2018), and the chance that global temperature increases will remain below 1.5ºC threshold by 2100 is less than 1% (Raftery et al., 2017).

Historically, there have been unequal emission releases within and across nations (Böhringer et al., 2015; Dietz et al., 2015; Edenhofer et al., 2014; Padilla & Serrano, 2006; Podobnik, 2002; Zhang et al., 2017), with no international governing body that can monitor and enforce emission reductions for countries (Zia & Koliba, 2011). This lack of governance has made emission reductions a global ‘tragedy of the commons’ problem (Dietz et al., 2003; IPCC, 2014). The absence of emission release accountability has given incentives for some governments and businesses to free ride on the hard mitigation work of others or avoid all but minor emission abatement costs (Lockie, 2013; Zia & Koliba, 2011). The disparity in emission releases has led to tensions between those who have historically released the climate changing GHGs and those who suffer the adverse effects of a changing climate (Alexander et al., 2011; Dankelman, 2002; Diffenbaugh & Burke, 2019; Farbotko & Lazrus, 2012; Ford et al., 2010; Gentle & Maraseni, 2012; Parks & Roberts, 2006). To address this disparity, the lack of global governance, and the pressing need to reduce emissions, the world engaged in the UN COP21 in late 2015 in hope to finding solutions. With over 190 participating countries, COP21 "aim(s) to achieve a legally binding and universal agreement on climate, with the aim of keeping global warming below 2°C" (Climate Action, 2015). Although it is now recognized that the global average temperature must remain below 1.5°C by 2100 to avoid moderate to severe catastrophic consequences of climate change (Hoegh-Guldberg et al., 2019; IPCC, 2018), the message from COP21 remains the same, nations must take calculated and immediate steps to reduce their emissions if the global community is to avoid the moderate to severe detrimental effects of climate change.

Given that nations are ultimately accountable for the total GHGs of all regions they govern, it is the sum of the outcomes of subnational and local policies and actions that comprise national GHG totals (Corfee-Morlot et al., 2009). There are many variables affecting emission variation at the subnational and local scales (IPCC, 2014), and many of these variables can be grouped into being political governance, socioeconomics, or weather-related categories. However, the effect that these variables have on GHG emissions remains both controversial and unclear. For example, a rising population is often cited as a major variable causing emissions to grow (Dietz et al., 2015; Rosa & Dietz, 2012; Shi, 2003). This claim is however challenged by opponents that propose that wasteful consumption, not population, is mostly responsible for growing emissions (Parks & Roberts, 2006; Stephenson et al., 2013; Wiedmann et al., 2020), and that population will play a minimal role in determining future emission trends (Raftery et al., 2017). Likewise, democratic processes are argued to be essential for the creation of effective environmental policy

(Carter, 2013) and lowering emissions (Jensen & Spoon, 2011). Others disagree, stating that these processes have had an inadequate, or even unfavorable, influence on lowering emissions (Bache et al., 2015; Böhmelt et al., 2016; Brown, 2012; Rabe, 2007; Steurer & Clar, 2015). Lastly, a changing climate is going to alter the energy use supply and demand, such as providing the heating and cooling of buildings, but how and where these energy supplies and demands will change remains unknown (Isaac & van Vuuren, 2009; Li et al., 2019; Santamouris, 2014; Steenhof & Weber, 2011; Ürge-Vorsatz et al., 2015; Yalew et al., 2020).

My thesis research is motivated by the uncertainties associated with the effects of political governance, socioeconomics, and weather factors on emissions as illustrated by the above examples. These uncertainties and the complexity of the processes involving GHG releases represent a major barrier for understanding the sources and pathways of GHG emissions, and the estimation of these emissions across political boundaries. Quantifying the political, socioeconomic, and weather drivers of GHGs is a necessary step for reducing emission variation uncertainties and identifying the sources of emission variation. It will help disentangle the complex and confounding relationships of the drivers of GHG emissions, thus facilitating better understanding of the complexity of climate change uncertainty while providing insights into the development of more effective emission reduction strategies.

1.4 Defining scales of study for this thesis

There are many challenges to quantify the relative importance of the drivers of GHG emissions, not least of which is choosing a geopolitical scale at which to quantify the resulting emissions. The variation in subnational emissions has not been traditionally considered in global emission reduction action (Edenhofer et al., 2014) but its importance is being increasingly recognized (Hsu et al., 2019; Hultman et al., 2020; Kuramochi et al., 2020). Connecting international and national emission reduction obligations with local initiatives allows for true understanding of emission reduction pathways (Corfee-Morlot et al., 2009). Furthermore, studying emissions across subnational regions offers considerable potential to limit emissions through cooperation because these regions are in close geographical proximity, are often guided by a common policy framework or have comparable policies, participate in investment and trade across borders, and rely on shared infrastructure (Edenhofer et al., 2014). These conditions are met by the Canadian provinces, which are the focus of this thesis. In addition to this provincial scale, my thesis also analyzes variation in GHG emissions at the community/municipal level.

Communities of differing sizes, but notably large urban centres (*i.e.*, cities), have become the epicentres of human life, innovation, and emission releases in the modern global environment (Bettencourt et al., 2007; Moran et al., 2018). Most of the world's population now live in urban environments (World Bank, 2017), with an estimated 6.9 billion people living in cities by 2050 (UN, 2014). Cities are also disproportionate hubs of human productivity with more than 80% of the global GDP and 70% of global CO_2 emissions accounted for in these areas (UN-Habitat, 2016). Since national emission totals are the sum of subnational emissions, and these subnational emissions are the sum of emissions from localized production and consumption, often within communities of differing sizes, community level jurisdictions provide another important scale of study to quantify the drivers of subnational emissions.

1.5 Thesis outline

My thesis investigates the political governance, socioeconomic, and weather drivers of GHG emissions across provincial and municipal jurisdictions in Canada. After framing the importance

GHG emission research above, my three data chapters begin by exploring the drivers of emissions across provincial jurisdictions, followed by how these drivers may change from provinces to municipalities, and ends with my third data chapter focusing on quantifying the variation in GHG emission across municipal jurisdictions. A brief overview and the relevance of each of my three data chapters are presented below.

In **Chapter Two**, I explore the relative effects that political governance, socioeconomics, and weather have on provincial GHG emissions across Canada. The results show that socioeconomics is the main driver of emissions across Canadian provinces, while political governance, measured by the political party that held office, had only a trivial effect on emissions. Where significant, the influence of political party was inconsistent but had a strong interaction with the regional economy. Of the socioeconomic factors, energy efficiency was the most influential, lowering GHGs in eight provinces. I conclude that socioeconomic factors are the most important drivers of emissions across Canada. Political governance had a limited capacity to influence GHG variation without considering the regional economy. Furthermore, investing in energy efficient technologies may have the greatest return in limiting GHGs.

In **Chapter Three**, I test how the drivers of GHGs change from the provincial to the municipal jurisdictions in Canada. This is done by modelling and then comparing the effects of political governance, household socioeconomics and weather on household emissions from electricity, natural gas, and petrol for province and city jurisdictions from 1997-2009. I show that socioeconomics are the strongest predictors of household emissions for both jurisdictions, while political governance, estimated by using established textual analysis methodologies on provincial Hansards and city council minutes, are only correlated with household emission variation at the city jurisdictional level. The results show that socioeconomics factors were most important, accounting for 15.6% to 49.0% of emission variation in cities and 66.6% to 75.2% in provinces. Political governance was only significant at the city level, contributing at most 4.8% to the variation, but had joint contributions with other variables, particularly socioeconomics. Overall, the drivers of household GHG emissions changed across jurisdictions and energy sources. I conclude that the integration of local, source specific policies into subnational and national based strategies is necessary to effectively limit GHGs.

In **Chapter Four**, I investigate how the factors that drive emissions change from smaller to larger GHG emitting communities by applying quantile regression to total and per capita consumption-based emission for 1679 communities across Canada in 2015 with demographic, socioeconomic, and household factors as independent variables. The motivation for this chapter is that communities of different sizes may have different emission patterns. Therefore, GHG emission policies that apply to large communities may not be effective for small communities, and vice versa. Thus, it is necessary to take account of the variation in community socioeconomic factors to make effective policy decisions. Quantile regression is an effective modeling tool to model this variation. The results show that population and affluence were the most important variables affecting total community GHGs, while affluence was the most important factor affecting per capita community GHGs. However, their effect sizes were not consistent across quantiles. The effect size decreased for population and increased for affluence from lower to higher community emission quantiles. Moreover, poverty was correlated with increases in per capita and total community GHGs for all quantiles at the national level. Overall, the importance of the factors driving CO_2 emissions varied across communities of different quantiles. I conclude that successful emission reduction policies must consider the differences between communities, particularly by considering the variation in population and affluence of communities. In addition, poverty alleviation may be an effective means to lower emissions and should be considered in community-based climate mitigation and adaptation policies.

In summary, my thesis provides research that quantifies the effects of political governance, socioeconomics, and weather on GHG emissions across different jurisdictional levels, from local communities to provinces. It identifies the sources of variation in GHG emissions across those jurisdictions and provides insights that may be helpful in future emission reduction policy creation. For example, my exploration into how the drivers of emissions change across vertical and horizontal subnational jurisdictions can be useful to better integrate subnational emission reduction actions with national and international climate change adaptation strategies. Overall, my thesis allows for a more complete understanding of emission variation across Canada, the factors affecting this variation, and contributes suggestions to limit future GHG emissions.

Chapter Two: Political governance, socioeconomics, and weather influence provincial GHG emissions in Canada

2.1 Abstract

Quantifying the effects of political, socioeconomic, and weather factors on greenhouse gas (GHG) emissions is vital for successful climate change mitigation and adaptation. We modeled these effects on provincial per-capita GHG emissions across Canada from 1990 to 2019. The results showed the percentage of variation in GHG emissions explained by the models ranged from 75.3% to 98.8% across the ten Canadian provinces. Socioeconomics was associated with most of the emission variation (46.1%), followed by weather (1.4%). The effect of political governance on GHG emissions was minor (0.7%) and inconsistent but had a strong interaction with socioeconomic factors. Energy use efficiency was identified to be the most influential factor, contributing to lowering emissions in eight provinces. We conclude that socioeconomic factors are most important in causing GHG emissions across Canada, while the importance of political governance is trivial, much to the chagrin of those making election promises. Investment in energy efficient technologies should have the highest return in reducing emissions.

2.2 Introduction

Anthropogenic greenhouse gases (GHG) affect the global climate, causing serious threats to humanity and the global biosphere (Diffenbaugh and Burke, 2019; Steffen et al., 2018). While there are potentially numerous anthropogenic factors that directly or indirectly contribute to the emission of GHGs (Edenhofer et al., 2014), these factors can largely be grouped as political, socioeconomic, or weather related, with the latter as a natural factor that could have a direct effect on energy production and consumption. The intertwining of these factors form complex effects on GHG emissions (Rosa and Dietz, 2012), e.g., politics may impact GHG emissions directly via emission targeted policy (Eskander and Fankhauser, 2020; Martin and Saikawa, 2017) or indirectly via changes in the regional economy through job creation policies or other measures (Dietz et al., 2015). Furthermore, variation in weather can impact the supply and demand of energy (Schaeffer et al., 2012), causing additional emission variability. Disentangling the effects of these factors and their interactions is elusive but necessary not only for identifying critical knowledge gaps for developing mitigation policy and measures, but also for reconciling previous conflicting findings on the effects that different factors have on GHG emission releases (Bache et al., 2015; Böhmelt et al., 2016; Dietz et al., 2015; Jensen and Spoon, 2011; Rabe, 2007; Raftery et al., 2017).

Past investigations into the factors that affect emission variation have provided mixed results. For example, in the US, states with more frequent pro-environmental voting within their Congressional delegations have less drastic increases in emissions over time (Dietz et al., 2015) and political parties with more focused environmental concerns in their platforms advance more quickly towards reaching Kyoto targets (Jensen and Spoon, 2011). However, short election cycles may cause politicians to favour tangible short-term job creation and economic growth at the expense of upholding medium to long-term pro-environmental policies (Bache et al., 2015), while democratic inclusiveness can lead to the establishment of climate change-related policies with no significant emission reductions (Böhmelt et al., 2016). The prioritization of economic growth by governments means that the economic and demographic factors that interact with political decision-making could seriously influence the establishment and implementation of emission mitigation policy.

Economic growth and changes in population are partially influenced by political decision-making through policies on job creation, immigration, etc., but the degree to which economic growth and population drive emissions is still being resolved (Dietz et al., 2015; Jorgenson et al., 2019; Rosa and Dietz, 2012). Economic growth leads to higher levels of consumption, causing increased emissions (Sudmant et al., 2018), but it can also decrease emissions by increasing investment in pollution abatement, green technologies, and infrastructure (Panayotou, 1997). Similarly, the relationship between growing populations and emission trends could be affected by both economies and diseconomies of scale, such as emission decreases from public transit use or increases from more traffic congestion, or by other factors such as changes in age structure (Rosa and Dietz, 2012). Additionally, people living in more populated areas have lower per-capita energy demand because their homes tend to be smaller (Glaeser and Kahn, 2010) and lower energy use from utility consumption in shared multi-unit dwellings (Brown et al., 2009), but may increase per-capita emissions due to greater productivity in urban environments (Oliveira et al., 2014) or through an increase in household consumption linked to higher urban incomes (Heinonen and Junnila, 2011). Moreover, population growth may not be a major driver of emissions in the future (Raftery et al., 2017).

In addition to the effects of population and socioeconomics, weather conditions can have near-immediate effects on energy consumption. Energy security concerns are intensifying as people become ever more dependent on indoor climate systems, e.g., heating and air conditioning (Davis and Gertler, 2015; Edenhofer et al., 2014). Likewise, changes in precipitation affect both renewable and thermal energy production (Yalew et al., 2020), while causing more frequent and destructive natural disasters where new resources will need to be procured to rebuild and protect communities threatened by these disasters (Ibarrarán et al., 2009), raising energy consumption, and thus emissions, in the process.

The intertwined complexity of political governance, socioeconomics, and weather on GHG emissions mean that the effect of any of these factors can be contingent upon the others and could be either negative or positive, making inference on their individual effects elusive and challenging. Furthermore, it is important to determine if emission declines are purposeful or due to secular trends in the economy (Le Quéré et al., 2019) and/or changes in weather. Much valuable research has been conducted on political governance, socioeconomics, and weather, but these studies do not attempt to holistically disentangle the complex effects of all three variable categories on emissions, instead focusing on one or two of these categories in any given study. In addition, discussions focusing on the ability of political governance to influence emissions are often qualitative, lacking quantitative support in the discussions. This is especially the case when discussing the roles of different political parties in limiting emissions (Carter et al., 2018). In studies where quantitative evidence is provided, these studies tend to center on empirical differences at the national level or classify political parties simply as being left or right wing (Hu et al., 2021), neglecting the difference of individual parties and their related policies.

The complexity of the influences of political, socioeconomic, and weather factors on GHG emissions and the lack of quantitative understanding of these effects call for disentangling these effects to make evidence-based climate mitigation policies. In this study, we present an analysis on GHG emissions in Canada with the aim to quantify the relative contributions of political, socioeconomic, and weather factors to GHG emissions. We quantify the effects of factors which include provincial political parties, per-capita GDP, price of oil, precipitation, and temperature on per-capita GHG emissions for each of the ten Canadian provinces as well as the whole country with all provinces pooled from 1990 to 2019. Our results show that socioeconomic factors are most important in affecting GHG emissions, with the variable measuring energy use efficiency being the single most influential factor. This suggests that investment in energy efficient technologies should provide the highest return in lowering emissions. In addition, changes in political parties holding office are trivially and inconsistently associated with per-capita emission trends, being limited by the status quo of the regional economic environment.

2.3 Methods

2.3.1 Data

We modeled annual per-capita tonne of CO2 equivalent (CO2eq) GHG emissions as a function of political, socioeconomic, and weather predictors for each of the 10 Canadian provinces from 1990 to 2019. The Canadian territory jurisdictions have been excluded from this study because their political structures differ from that of the provinces. GHG emissions were obtained from published sources (Environment and Climate Change Canada, 2021; Table 2.1, Section 2.7). The political, socioeconomic, and weather data are described below.

Political governance data: Provincial general election voting records from 1990 to 2019 were obtained from each province's official election records websites (see Elections Alberta, 2022; Elections BC, 2022; Elections Manitoba, 2022; Elections New Brunswick, 2022; Elections Newfoundland and Labrador, 2022; Elections Nova Scotia, 2022; Elections Ontario, 2022; Elections Prince Edward Island, 2022; Elections Québec, 2022; Elections Saskatchewan, 2022). These records were used to determine which political party was the governing party for each year within each province from 1990 to 2019. In a year with a provincial election, when two political parties can hold office at different times during that year, the party that held office longer was assigned to that year. The political parties were coded as character variables containing all elected provincial political parties from 1990 to 2019. These elected political parties consist of the following parties: Liberal (Lib), New Democratic Party (NDP), Parti Québécois (PC), Progressive Conservative (PC), and Saskatchewan Party (SP). Due to a limited number of years holding office, observations containing Social Credit Party in British Columbia for the years 1990 and 1991, United Conservative Party in Alberta for the year 2019, and Coalition Avenir Québec in Québec for the year 2019 were removed (see Figure 2.5, Section 2.7 for a general representation of where each party lies on a left-right political spectrum).

Socioeconomic variables: Socioeconomic data were collected and compiled from multiple tables provided online by Statistics Canada (2022a, 2022b, 2022c, 2022d). Where difficulties in finding data online arose, Statistics Canada was contacted directly through their web portal for assistance in obtaining data. We obtained provincial level data on GDP from Statistics Canada Table 36-10-0222-01 (reported as chained 2012 values), population from Table 17-10-0005-01, and total annual primary and secondary energy demand from Tables 25-10-0004-01 and 25-10-0029-01 (Figures 2.6 and 2.7, Section 2.7). The data from Table 25-10-0004-01 were reported in quarterly values. The four quarters for each year were summed to obtain annual values. British Columbia and Québec did not have total energy demand reported for the year 2017 due to energy data being suppressed to meet the confidentiality requirements of the Statistics Act. These two observations were removed due to this incomplete data.

Following recommendations in the literature (Liobikienė and Butkus, 2019; Panayotou, 1997; Taylor et al., 2001), socioeconomics was grouped into three variables: scale of the economy, sectoral composition of the economy, and energy efficiency. The scale of the economy is required to support a growing economy (Panayotou, 1997), leading to greater emissions as the economy grows. We use per-capita GDP to represent the scale effect. The sectoral composition of the economy is a measure of the changes in the allocation of resources from one sector of society to another (Panayotou, 1997). A shift in the sectoral composition towards a more industrial economy will likely intensify the procurement and processing of regional raw resources (Panayotou, 1997), thus increasing emissions (Tian et al., 2014). We use the industrial energy demand to total energy demand ratio as our measure of the compositional effect. The advance in new and energy efficient technologies can affect emissions in several ways. First, increased adoption of new technologies will lead to more efficient means of producing and consuming goods, lowering emissions (Jordaan et al., 2017). Second, increased adoption of more efficient technologies within exploitive industries will increase emissions because previously inaccessible resources can now be exploited once these new technologies are introduced (Martin et al., 2016). Third, energy efficiencies may encourage a "rebound effect", an effect where emissions increase because of an increase in consumptive behaviours from the adoption of new technologies (e.g., driving a vehicle more often because it is 'fuel efficient') (Gillingham et al., 2013). Our technological efficiency effect is represented by GDP per unit of total energy usage. Additionally, the price of oil was included to account for emission variation attributed to changes in economic activity outside of Canada, exemplified through an exploratory analysis showing there was a linear correlation between the price of oil and the GDP of Canada ($r2$ = 0.627) from 1990 to 2019. The price of oil was originally reported in nominal US$ and converted to 2012 US$ using the Implicit Price Inflator index (Bureau of Economic Analysis, 2022; U.S. Energy Information Administration, 2022).

Weather variables: Data on temperature and precipitation were collected from weather stations in each province maintained by Environment and Climate Change Canada (2022; Figure

2.8, Section 2.7). Mean temperature and precipitation for each province were then calculated for the months of January (the coldest month) and July (the warmest month), as well as annually, from 1990 to 2019. Due to the unavailability of precipitation data for the years 2018 and 2019 in the database of Environment and Climate Change Canada, we used precipitation data from the Daymet database (Thornton et al., 2020) for these two years in all provinces, with Prince Edward Island requiring additional data for 2012 to 2017 from Daymet. To ensure the validity of using Daymet data to fill in the missing precipitation data, we did Pearson's correlations of the precipitation data of the two databases across the locations of the Environment and Climate Change weather stations for those years when data were available, showing that January, July, and annual precipitation had $r2$ values of 0.923, 0.905 and 0.965, respectively.

2.3.2 Statistical analysis

Per-capita GHG emissions were modeled for each province and Canada as a whole. The data for Canada were pooled across all provinces. Numeric explanatory variables were normalized for each province and Canada to a range of 0–1 by (x – xmin)/(xmax – xmin). To assess collinearity among variables, we calculated correlation coefficients among the variables and, for any pair of the variables with $r2 > 0.90$, one was removed. The technological efficiency and scale variables were found to be collinear for five provinces (*i.e.*, BC, MB, ON, QC, and NL), where the scale variable was removed. The dependent variable (*i.e.*, per capita GHG) was log-transformed and modeled with a multiple linear regression model for each province and Canada, with the political, socioeconomic, and weather factors as independent variables. The quadratic forms of the composition, technological efficiency, and scale variables were also included as independent variables. While checking the adequacy of the models, temporal autocorrelation and/or heteroscedasticity in model residuals were detected in some provinces and Canada. We thus re-fit these models by including a first-order autoregressive term to account for temporal autocorrelation and a variance structure to take account of inhomogeneous variance. The form of the full models is:

$$Y_i = \beta_0 + \beta_1 government_i + \beta_2 oil_i + \beta_3 composition_i + \beta_4 technology_i + \beta_5 scale_i + \beta_6 composition_i^2 + \beta_7 technology_i^2 + \beta_8 scale_i^2 + \beta_9 anntemp_i + \beta_{10} jantemp_i + \beta_{11} jultemp_i + \beta_{12} annprecip_i + \beta_{13} janprecip_i + \beta_{14} julprecip_i + \beta_{15} government_i \cdot composition_i + \beta_{16} government_i \cdot technology_i + \beta_{17} government_i \cdot scale_i + \phi Y_{i-1} + \varepsilon_i, \quad (2.1)$$

where i = 1, 2, …, 30 indicating the years from 1990, 1991, …, to 2019, respectively. For British Columbia, Québec, and Alberta, not all years from 1990 to 2019 are included because of missing data in some years (see Methods above). φ is the first-order autoregressive coefficient. The residuals ε_i may or may not meet the homogenous normal distribution assumption, depending on the province being modeled (see Table 2.2, Section 2.7 for the variance structure of each model). Because the numeric explanatory variables are standardized to a (0, 1) range, the size of the coefficients' βs (called effect size) are directly comparable for the effect of each variable on GHG emissions in each model. The results for each full model are shown in the Supplementary Information (Table 2.3, Section 2.7).

A backward selection process was used to select the "best" model for each province and Canada. This was done by removing the variable with the highest p-value. The procedure was repeated until all remaining variables had p-values smaller than 0.10, the variables were part of a significant interaction term, or their quadratic forms were significant. To ensure that the removed variables did not collectively affect emission variation, we conducted a log likelihood ratio test (a $\chi 2$ test) on our full and selected Canada country models. This provided a *p*-value of 0.818, confirming the effectiveness of the backward selection procedure in excluding variables that did not contribute to GHG emissions. We further followed the method of Legendre (2008) to conduct variation partitioning to quantify the unique and shared contribution of politics, socioeconomics, and weather on emissions in each province and the whole country. All statistical analyses were conducted using R software (R Core Team, 2020). Specifically, generalized least squares were conducted using the *gls* function in the R package *nlme* (Pinheiro et al., 2017) and variation partitioning was conducted using the *varpart* function in the R package *vegan* (Oksanen et al., 2018). Additional details on the regression modelling are included in Supplementary Information, Section 2.7.

2.4 Results

Per-capita emissions across provinces varied considerably from 9.6 to 75.8 tonnes per year (mean = 26.9, standard deviation = 20.4). Socioeconomics made a greater contribution than any other variable category to GHG emissions pooled across Canada (46.1%), followed by weather (1.4%) and government (0.7%) (Figure 2.1, first panel). The sources of the variation for the rest 51.8% were attributed to a joint contribution (41.7%) of two or more variable categories or was unidentified (10.1%). Socioeconomics also made the greatest individual contribution to the emitting of GHGs within each province. Political governance overall had small, negligible contributions to the explained GHG variation (Figure 2.1). Furthermore, within- and between-party emission variations were not dependent on the relative position of the parties on the political spectrum (Figures 2.1–2.3). Weather was associated with total per-capita emission variation in eight provinces and accounted for no more than 9.3% of the variation in any given province. There was a substantial joint contribution between political party and socioeconomics in some of the provinces, especially in Saskatchewan (57.3%; Figure 2.1).

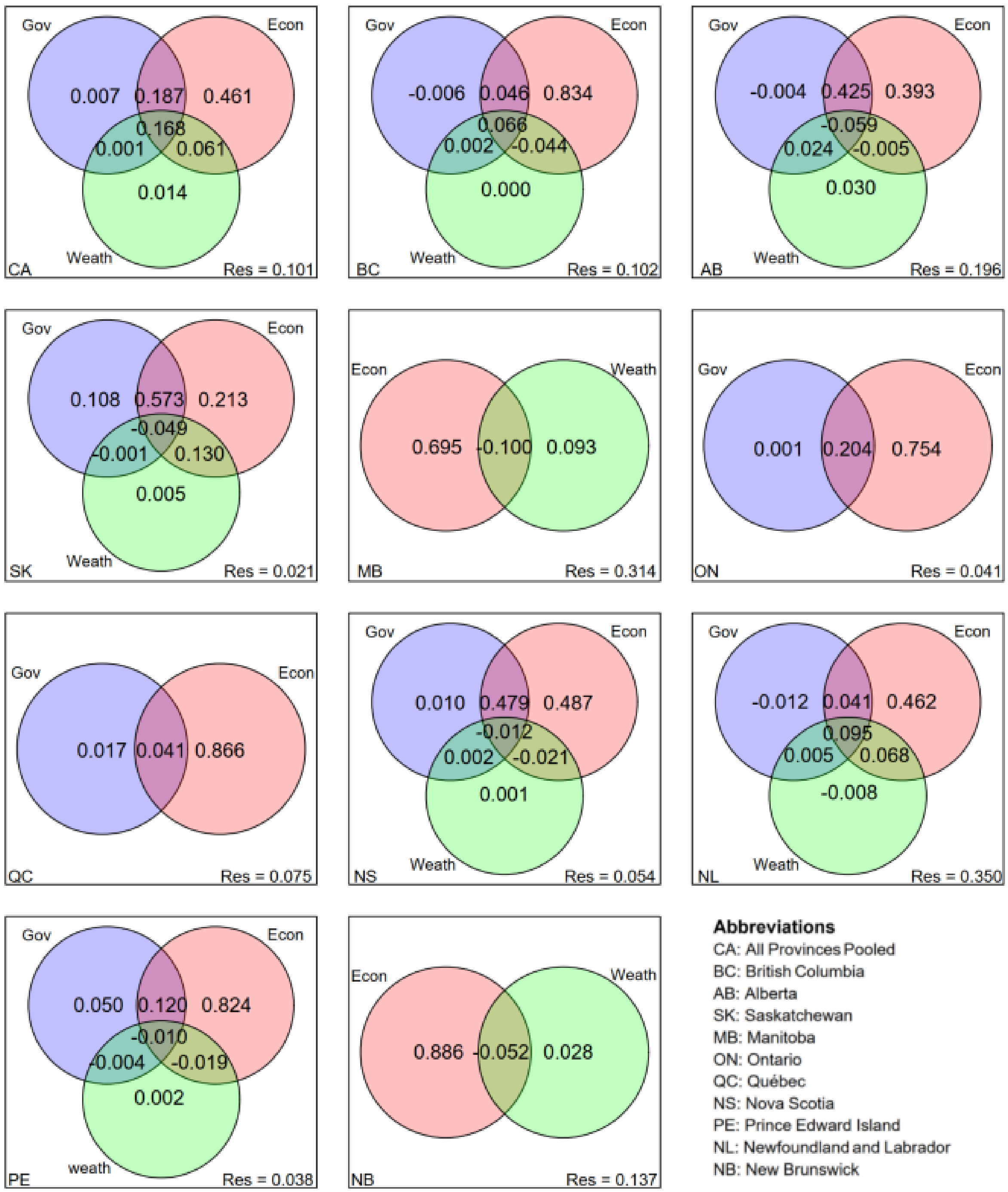


Figure 2.1| Venn diagrams showing the variation partitioning of significant government (blue), socioeconomic (red), and weather (green) variable categories for each province and

all provinces pooled (i.e., Canada) from 1990 to 2019. The values describe the amount of explained variation each variable category was associated with in relation to total variation in log-transformed per-capita GHG emissions. A joint contribution is represented by the overlap of circles. Negative joints, per the method, are interpreted as zeros (Legendre, 2008). Residual variation is given in the bottom right corner of each diagram and describes the per-capita emissions variation that is not attributed to any variable included in the analysis.

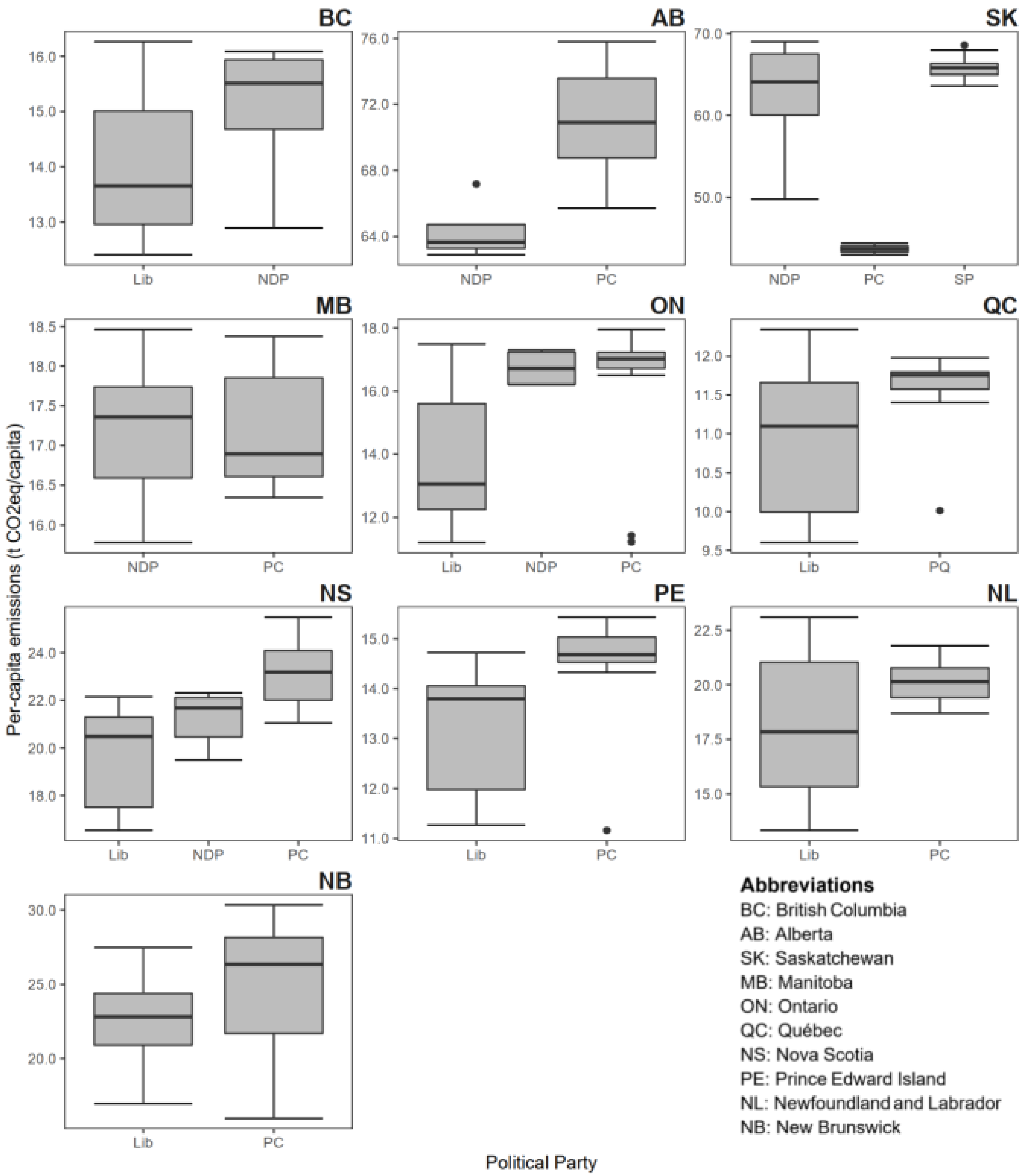


Figure 2.2| Box plots showing the range of annual tonne per-capita CO2eq emissions that were produced while each political party held office in each province from 1990 to 2019. The effect that each political party had on emission variation was assessed in the main text. Emission scale is differing across provinces. The abbreviations for the political parties are

New Democratic Party (NDP), Parti Québécois (PC), Liberal (Lib), Saskatchewan Party (SP), Progressive Conservative (PC).

Of the socioeconomic variables (Figure 2.3; Table 2.4, Section2.7), energy efficiency dominated, being significantly associated with per-capita emissions in all provinces except Saskatchewan. Of the provinces where energy efficiency was significant, it was associated with lower emissions except in Manitoba, Québec, and Newfoundland and Labrador. Manitoba and Québec had positive coefficients for energy efficiency yet negative coefficients for its quadratic term. In Newfoundland and Labrador, energy efficiency was associated with an increase in emissions. Economic composition was significant (p-value < 0.05) or marginally significant (p-value < 0.1) in eight provinces, but its influence was province specific, with positive coefficients in five provinces and negative coefficients in three provinces. Additionally, the composition quadratic term was significant in four provinces, having a negative coefficient in British Columbia, Ontario, and New Brunswick, and a positive coefficient in Manitoba. Economic scale was consistently positive and strongly associated with per-capita emissions in five provinces, while the scale quadratic term was present with a negative coefficient in three provinces. The effect of weather was significant in eight provinces where high July temperatures were consistently associated with increased emissions. High January and annual temperatures were associated with low emissions in Saskatchewan, Manitoba, and Newfoundland and Labrador, but a high January temperature in British Columbia, Prince Edward Island, and across Canada had a small yet significant positive effect on emissions (Figure 2.3). High precipitation in a year or in July were correlated with increased emissions in all instances except Nova Scotia where an increase in annual precipitation decreased emissions, while increased January precipitation decreased emissions in all instances. Elected political party or its interactions with other factors were significant or marginally significant in eight provinces, but again, the direction and magnitude of the effect on emissions was province contingent (Figures 2.3 and 2.4; Table 2.4, Section 2.7). For example, Progressive Conservative was associated with the lowest per-capita emissions of any political party in Saskatchewan but the highest emissions in Alberta.

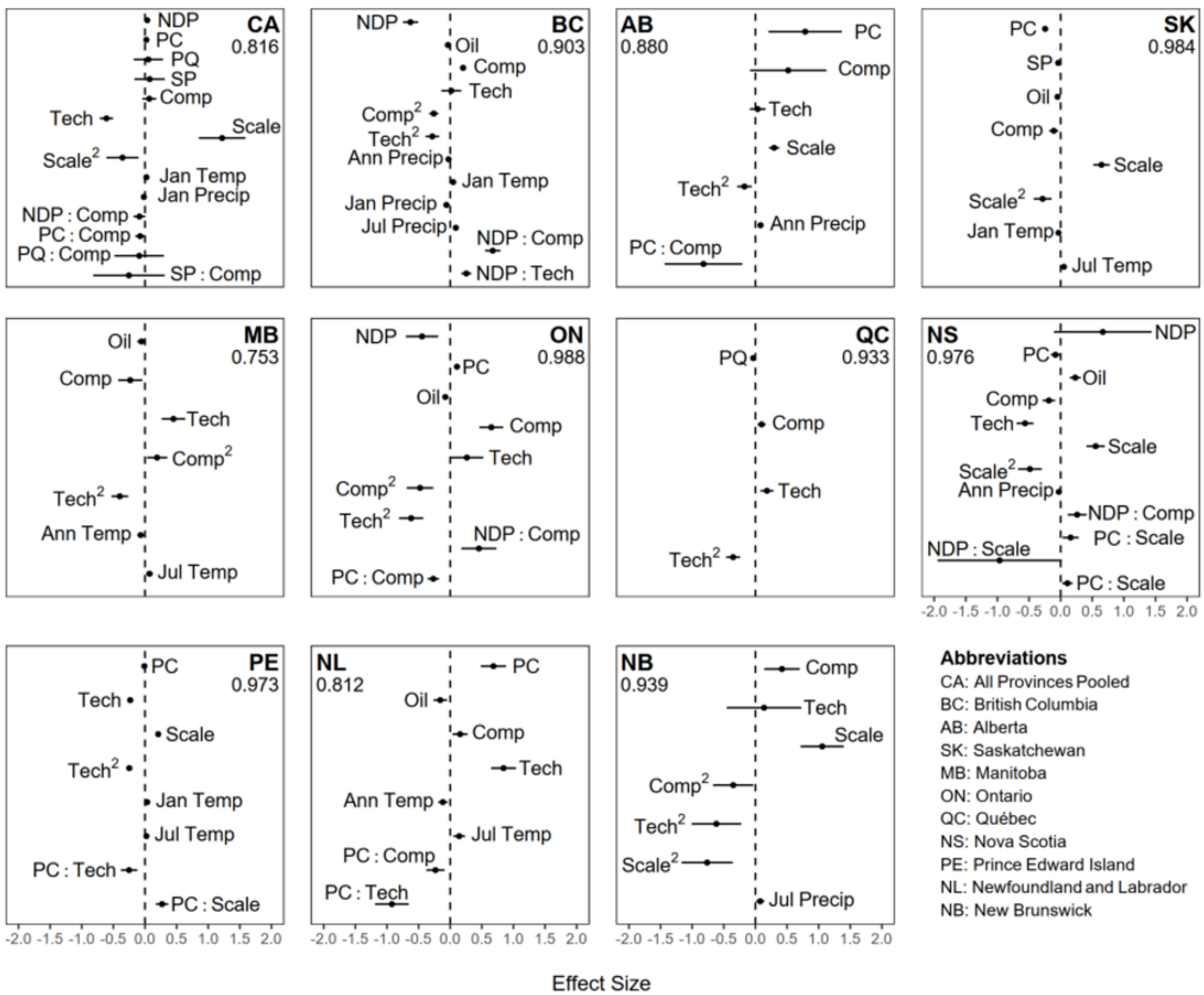


Figure 2.3| Effect sizes (and the 95% confidence interval) of independent variables on per-capita emissions for each province and Canada (i.e., all provinces pooled) from 1990 to 2019. If the 95% interval crosses over the zero vertical dashed line, that variable is non-significant. An adjusted *r*2 value that measures the correlation between the predicted per-

capita emissions and the observed emissions is presented under each province abbreviation. Liberal party was the baseline party for the categorical variable "political party" except for AB, SK, and MB where New Democratic Party was the baseline.

2.5 Discussion

The global community is currently consuming ecological goods and services at a rate that neglects the limits of what the Earth can provide (Martin et al., 2016), releasing GHG emissions to supply this consumption. Regional policies have the potential to provide effective solutions to limit these emissions (Deetman et al., 2015), but the full potential for this has not yet been realized (Edenhofer et al., 2014; Schreurs, 2008). Quantifying and understanding the relative importance of the different drivers of emissions is critical to developing effective emission reduction policies (Heinonen et al., 2020; UNEP, 2018). It has been argued that elected political parties are strong influencers of emission reduction trends (Jensen and Spoon, 2011). Our results however show that elected political parties across the Canadian provinces are weakly associated with GHG emission reductions at best or do not affect emission at all (Figures 2.1 and 2.3; Table 2.4, Section 2.7). Our study instead shows most emission variations were strongly associated with socioeconomics or the joint effects of political governance and socioeconomics. Moreover, even where political affiliation contributed to emission variations, the effect size of specific political parties was not consistent across provinces and was largely influenced by the regional economy. This finding suggests provincial change in political governance is unlikely to influence emission outcomes independent of the regional economy. Of all the factors affecting GHG emissions, the development and dispersion of energy efficient technologies appears most effective in reducing emissions.

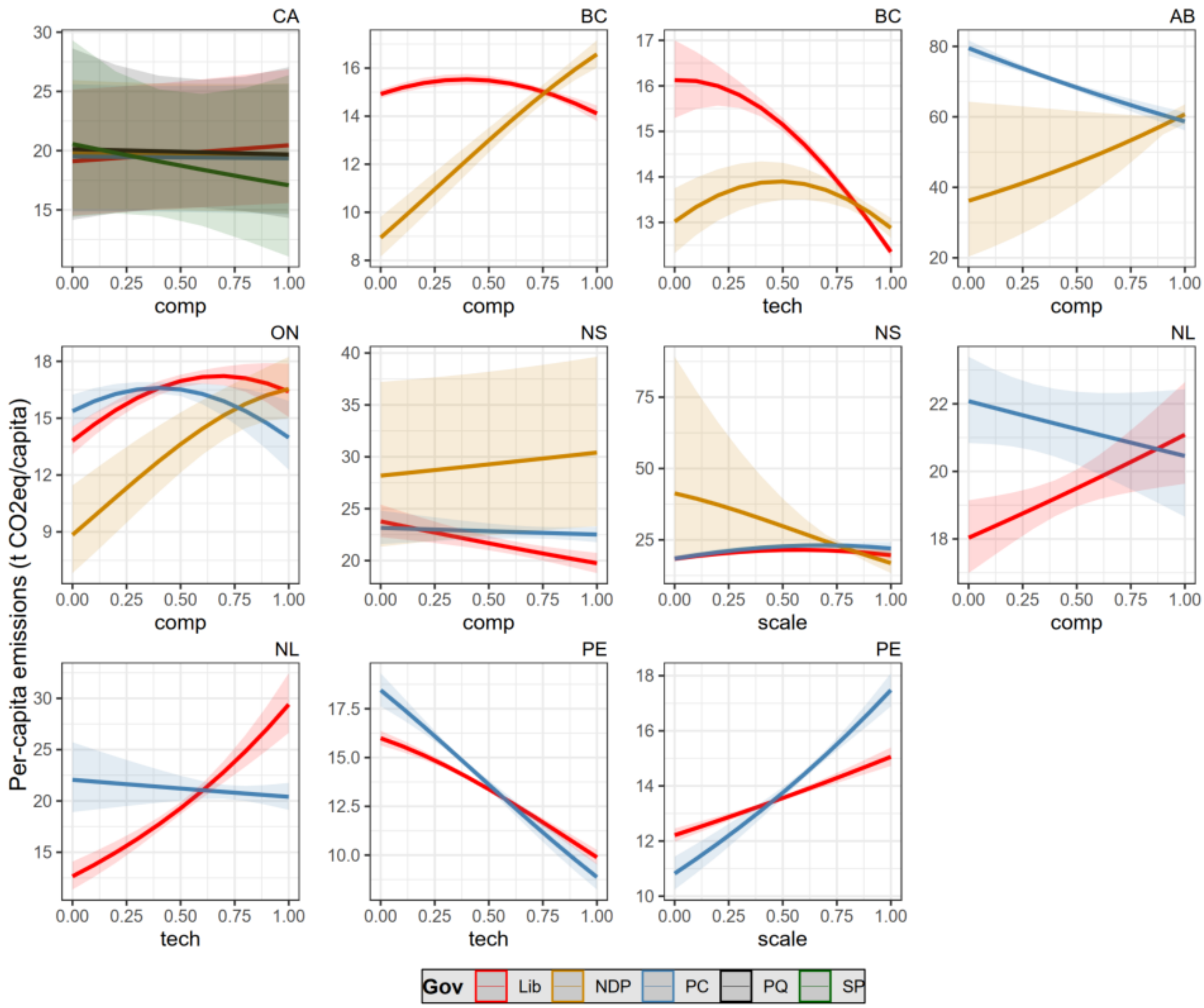


Figure 2.4| Interaction plots between political party and socioeconomic variables where the interaction terms are significant. The greater the difference in slope between two political parties, the more significant the interaction. Near parallel lines indicate no significant interaction. Curved lines show the influence of the quadratic term for that socioeconomic variable. The response variable has been back-transformed to show per-capita kilotonne of CO_2 equivalent (CO_2eq) GHGs. Shaded areas are the 95% confidence interval for each political party. The socioeconomic variables are scale of the economy (scale), sectoral composition of the economy (comp), and technological efficiency (tech).

2.5.1 Socioeconomics was the main influence on emission variation

We found that the scale variable was strongly associated with increased emissions, as expected, while the directions of the effects of the composition and energy efficiency variables on per-capita emissions were regionally dependent, changing from one province to the next (Figure 2.3; Table 2.4, Section 2.7). Such inconsistencies across socioeconomic drivers of GHG emissions are common within and across studies (Tsurumi and Managi, 2010).

Most provinces saw a strong association between energy efficiency and a decrease in per-capita emissions. This finding is consistent with the findings of other studies where energy efficiency contributes to lowering emissions (Liobikienė and Butkus, 2019; Mohapatra et al., 2016). This suggests that the promotion of the societal adoption of energy efficient technologies is a key strategy to reduce emissions (Liobikienė and Butkus, 2019; Schreurs, 2008), but such a strategy should also consider human behaviour to ensure that the most effective technologies are promoted (Adua et al., 2019; York, 2012). For example, Newfoundland and Labrador showed that an increase in per-capita emissions was associated with an increase in efficiency, at odds with the results of other provinces but consistent with the argument that the introduction of more efficient resource extraction technologies can inflict environmental damage through the exploitation of previously inaccessible resources (Martin et al., 2016). Furthermore, the hydropower producing provinces Manitoba and Québec had positive coefficients for energy efficiency but negative coefficients for the quadratic of energy efficiency, indicating initial investment in energy efficiency increased emissions but that effect was reversed with further investment. This likely happened because of the increased emissions during the early phases of hydropower production where the construction of infrastructure and the development of the supply chain take precedent, followed by the lower direct emissions produced from energy production once a hydropower plant is in full operation (Schlömer et al., 2014).

Regions with a strong industrial sector are generally more energy intensive than regions that focus on other economic sectors (Liobikienė and Butkus, 2019), leading to the release of more emissions (Tian et al., 2014). Our study only partially supports this finding where six out of eight provinces with the composition variable showed that an increase in the industrial composition of the economy was associated with an increase in per-capita emissions (Figure 2.3; Table 2.4, Section 2.7). Surprisingly, Saskatchewan, a province with heavy fossil fuel development, showed decreased per-capita emissions as the provincial economy became more industrialized. This result may be partially driven by an 1.5% decline in population from 1990 to 2006 and then an 18% sharp increase in population from 2006 to 2019, likely due to the increase in crude oil exploitation during this period of time (Canada Energy Regulator, 2022). The case of Saskatchewan exemplifies the importance of making regionally based emission policies.

2.5.2 The political economy of emissions

During election time, politicians communicate to the public their party's policy pledges and agendas, offering election promises in a bid for votes. In general, the public have an impression that political parties known to be more left leaning are often more environmentally friendly than right leaning parties (Hu et al., 2021; Neumayer, 2004). Such an impression is expected to translate into measurable differences in environmental outcomes between left and right parties if a political party fulfills its election promises. However, our study shows that this general impression does not actually transform into measurable GHG emission reductions after a party becomes elected. Political governance has little or no effect on GHG emissions and, where there is an effect, the effect is contingent upon the regional economy (Figures 2.1–2.4). This result is consistent with some studies but not with others. For example, it has been reported in the US that state senators are more likely to vote against climate stewardship policies if the state they represent have large stakes in coal mining development, regardless of political affiliation (Fisher, 2006). It has similarly been shown that the representational effect of green politicians in national parliament was insignificant in predicting GHG emissions when economic factors were also considered (Lægreid, 2014). In studies that report results inconsistent with ours, they found that pro-environmental voting and political platforms did affect emissions by slowing down the release of these emissions (Dietz et al., 2015; Jensen and Spoon, 2011). Notwithstanding, economic growth and job creation policies are favoured by political parties over policies promoting long-term environmentally sustainable action, irrespective of where these parties lie on the political spectrum (Bache et al., 2015). Furthermore, the extensive technological lock-in of fossil fuels to provide energy solutions for society, and the sheer economic and political power of the fossil fuel industry, provide further resistance to reduce the societal dependence on high carbon-emitting energy sources (York, 2012). This suggests that, regardless of which party is elected, political representation through choice of political party has little to no influence on per-capita emission outcomes, undermining core tenants of representative democracy which imply that voters, and the parties they elect, matter in steering the trajectory of society. This inability of political parties to affect emissions independent of the regional economy is a serious barrier to effective climate change mitigation and adaptation because the economic status quo that drives GHG emissions will be upheld irrespective of the political party elected to represent the will and the needs of the people.

2.5.3 Conclusions and policy implications

Given that our results show that socioeconomic factors are the main drivers of emissions, our study suggests that measures focusing on the socioeconomics of GHG emissions are most effective in limiting emissions. Specifically, economic policies that target and promote investment in innovative green and energy efficient technologies, such as providing accessible subsidies that support public use of these technologies (Jordaan et al., 2017), will be key to adapt the needs of the society to the risks of climate change. Such technologies, like those found in the clean energy movement, are already propelling a decoupling of emissions and economic growth in the United States (Obama, 2017), but the current deployment of these technologies is insufficient to curb the moderate to severe effects of climate change (Millar et al., 2017) without government intervention and enforcement of stringent emission reduction legislation (Haberl et al., 2020). Moreover, further research into identifying which of these technologies to promote and deploy is necessary for successful policy development, as some energy efficient technologies have been shown to increase, instead of decrease, emissions (Adua et al., 2019). Furthermore, policies supporting energy efficient technologies should strategically consider how these technologies may be affected by changing weather patterns, as weather affects both production and consumption-based emissions including the production of renewable, low-carbon energy (Perera et al., 2020) and the consumption of energy for indoor climate control (Davis and Gertler, 2015; Edenhofer et al., 2014). This leaves much work for policymakers, and the limited ability of party politics to act effectively towards true emission reductions separate from the economy makes the situation even more difficult to navigate.

Our observation that political governance has little effect on GHG emissions separate from the economy raises serious concerns about the ability of the representational democratic process to instigate successful emission reduction and climate change mitigation policies. Governments are falling short of fulfilling their social contracts with their citizens (Adger et al., 2013) by failing to enact effective legislation that allow for the necessary societal changes required to reduce emissions and protect their citizens from climate change harm (UNEP, 2018). Short-term democratic election cycles impede these societal changes by encouraging politicians to prioritize short-term economic performance gains (Lewis-Beck and Stegmaier, 2000) and resist changes to the status quo that threaten the legitimacy of private economic incumbents (Paterson and P-Laberge, 2018), sacrificing established environmental policies in the process (Bache et al., 2015; Eckersley, 2017). The inability of differing political parties to be associated with changes in per-capita emission variation independent of private economic interests reinforces concerns that the democratic process in its contemporary form may not be capable of addressing the urgency of limiting global emissions (Bache et al., 2015; Rabe, 2007). However, we want to stress that these finding should not be perceived as a disincentive for voter participation. Instead, this provides quantitative support for voters to hold their governments accountable for lack of climate change action. Additionally, political parties can better monitor their own climate change successes and failures to ensure that policies that promote economic growth are not attained at the expenses of the loss of public health and irreversible environmental damage.

2.6 Supplementary information for Chapter Two

2.6.1 Regression modelling

All interaction terms between political party (government) and the socioeconomic variables of composition, scale and technique were included in model (1) presented in the main text. All models were optimized using generalized least squares. Each full model was inspected for temporal autocorrelation in the residuals using the *acf* function in R (R Core Team, 2020) and tested for heteroskedasticity. Models that showed evidence of temporal autocorrelation were re-fit with a first order autoregressive correlation structure. Models that showed evidence of heteroskedasticity were re-fit with a variance structure (Table 2.2). The Akaike Information Criterion (AIC) for the full model without any correlation structure was compared to the AIC of the models with correlation and variance structures. The model with the lowest AIC was chosen as the best model except in the situation where the difference in the AIC values was less than two, in which case the simpler model was chosen (Burnham and Anderson, 1998).

A backward selection procedure was conducted on each of the full models to choose the most parsimonious model for each province. This was done by removing variables with p-value > 0.10 until all remaining variables had a p-value < 0.10. We used a p-value cutoff of 0.10 to ensure all potentially influential predictors were captured in the models. To measure the goodness-of-fit for each model, the adjusted r^2 value from these regression models were reported. To test the unique contributions of political governance, socioeconomics, and weather to emissions, variance partitioning was calculated for models that had significant variables from at least two of these three categories for each province and for Canada.

2.6.2 Supplementary tables and figures

Table 2.1| Summary of data and their sources.

Variable Category	Data	Source
Dependent	Provincial annual GHG emissions (kt CO_2eq)	National Inventory Report 1990-2019: Greenhouse Gas Sources and Sinks in Canada – Part 3 (Environment and Climate Change Canada, 2021)
Political	Elected provincial political parties (1990 - 2019)	Provincial general election voting records from official elections websites (Elections Alberta, 2022; Elections BC, 2022; Elections Manitoba, 2022; Elections New Brunswick, 2022; Elections Newfoundland & Labrador, 2022; Elections Nova Scotia, 2022; Elections Ontario, 2022; Elections Prince Edward Island, 2022; Élections Québec, 2022; Elections Saskatchewan, 2022)
Socioeconomic	Provincial GDP	Statistics Canada (Statistics Canada, 2022a)
	Provincial annual population	Statistics Canada (Statistics Canada, 2022b)
	Total primary and secondary energy demand per sector (TJ)	Statistics Canada (Statistics Canada, 2022c, 2022d)
	Monthly first purchase price of barrel of crude oil ($US)	U.S. Energy Information Administration (U.S. Energy Information Administration, 2022)
Weather	Provincial daily temperature	Environment and Climate Change Canada (Environment and Climate Change Canada, 2022)
	Provincial precipitation	Environment and Climate Change Canada, Daymet(Environment and Climate Change Canada, 2022; Thornton et al., 2020)

Table 2.2| Variance structures for modeling the inhomogeneous errors for each of the models presented below. Subscript *j* in the Canada model represents each province where *j* = BC, AB, …, to NB, in year *i* = 1990, 1991, …, to 2019, respectively.

Model	Error Term Structure
Canada	$\varepsilon_{ij} \sim N\left(0, \sigma_j^2 e^{2\delta_{ij}}\right)$
British Columbia	$\varepsilon_i \sim N\left(0, \sigma^2 e^{2\delta \bullet tech_i}\right)$
Alberta	$\varepsilon_i \sim N(0, \sigma^2)$
Saskatchewan	$\varepsilon_i \sim N(0, \sigma^2)$
Manitoba	$\varepsilon_i \sim N(0, \sigma^2)$
Ontario	$\varepsilon_i \sim N(0, \sigma^2)$
Québec	$\varepsilon_i \sim N(0, \sigma^2)$
Nova Scotia	$\varepsilon_i \sim N\left(0, \sigma^2 e^{2\delta \bullet oil_i}\right)$
Newfoundland and Labrador	$\varepsilon_i \sim N\left(0, \sigma^2 e^{2\delta \bullet tech_i}\right)$
Prince Edward Island	$\varepsilon_i \sim N\left(0, \sigma^2 e^{2\delta \bullet scale_i}\right)$
New Brunswick	$\varepsilon_i \sim N(0, \sigma^2)$

Table 2.3| Effect of all variables and interaction terms on log transformed per-capita emissions. In modeling, Liberal was used as the baseline/reference party except for the provinces AB, SK and MB which had the New Democratic Party as the baseline/reference party. Since the continuous variables were standardized to (0, 1) range, the coefficients (effect sizes) are directly comparable. Standard errors are shown in parentheses. Some provinces had the scale variable removed due to collinearity. The provincial abbreviations are CA (Canada), BC (British Columbia), AB (Alberta), SK (Saskatchewan), MB (Manitoba), ON (Ontario), QC (Québec), NS (Nova Scotia), NL (Newfoundland and Labrador), PE (Prince Edward Island), and NB (New Brunswick).

	Dependent variable:										
	Emissions/capita log (kt CO2eq/person)										
	CA	BC	AB	SK	MB	ON	QC	NS	NL	PE	NB
NDP	0.061*	-0.559***				-0.655*		0.752			
	(0.034)	(0.103)				(0.352)		(0.568)			
PC	0.019		0.886**	-0.304***	0.039	-0.174		-0.117*	0.553	-0.018	-0.091
	(0.023)		(0.403)	(0.117)	(0.072)	(0.190)		(0.060)	(0.378)	(0.025)	(0.289)
PQ	0.312						-0.152				
	(0.386)						(0.142)				
SP	0.161			0.005							
	(0.189)			(0.067)							
Oil	-0.005	-0.028*	-0.018	-0.070*	-0.078	-0.078***	-0.034	0.292***	-0.133**	0.018	0.056
	(0.011)	(0.015)	(0.074)	(0.036)	(0.050)	(0.030)	(0.037)	(0.071)	(0.060)	(0.034)	(0.157)
Comp	0.130	0.176***	0.447	-0.212	-0.249	0.747***	0.041	-0.296**	0.419**	-0.019	0.372*
	(0.101)	(0.046)	(0.523)	(0.264)	(0.178)	(0.133)	(0.116)	(0.146)	(0.198)	(0.084)	(0.214)
Tech	-0.597***	0.016	0.071	-0.076	0.589**	-0.037	0.243***	-0.224	1.114**	-0.250**	-0.109
	(0.120)	(0.100)	(0.149)	(0.169)	(0.248)	(0.333)	(0.092)	(0.449)	(0.481)	(0.118)	(0.527)
Scale	1.232***		0.533	0.609***				0.405*		0.282**	1.014***
	(0.213)		(0.414)	(0.218)				(0.226)		(0.126)	(0.320)
Comp^2	-0.142	-0.219***	-0.001	0.053	0.211*	-0.674***	0.059	0.044	-0.283	0.022	-0.382*
	(0.111)	(0.069)	(0.143)	(0.219)	(0.127)	(0.214)	(0.132)	(0.136)	(0.192)	(0.070)	(0.231)
Tech^2	-0.014	-0.280***	-0.073	0.075	-0.483***	-0.438**	-0.419***	-0.353	-0.374	-0.186	-0.520
	(0.100)	(0.077)	(0.099)	(0.123)	(0.147)	(0.194)	(0.094)	(0.340)	(0.590)	(0.123)	(0.318)
Scale^2	-0.276*		-0.062	-0.206				-0.413**		-0.127	-0.628
	(0.146)		(0.139)	(0.165)				(0.168)		(0.141)	(0.459)
Ann Temp	-0.006	-0.001	0.022	0.005	-0.104**	-0.017	-0.045	0.038	-0.196***	0.008	0.035
	(0.022)	(0.030)	(0.039)	(0.032)	(0.050)	(0.034)	(0.036)	(0.044)	(0.049)	(0.011)	(0.073)
Jan Temp	0.023*	0.045***	-0.004	-0.019	0.023	0.009	0.034	-0.024	0.116*	0.025	-0.053
	(0.013)	(0.015)	(0.037)	(0.029)	(0.037)	(0.045)	(0.031)	(0.019)	(0.067)	(0.018)	(0.071)

Jul Temp	-0.001	0.009	-0.023	0.079**	0.082**	0.001	0.067	-0.001	0.139***	0.012	0.003
	(0.012)	(0.012)	(0.035)	(0.036)	(0.040)	(0.028)	(0.042)	(0.033)	(0.053)	(0.013)	(0.079)
Ann Precip	-0.018	-0.027	0.060	-0.040	0.035	0.005	-0.012	-0.050***	0.023	0.015	-0.084
	(0.017)	(0.017)	(0.044)	(0.026)	(0.056)	(0.032)	(0.027)	(0.017)	(0.041)	(0.011)	(0.076)
Jan Precip	-0.013	-0.054***	0.001	0.026	0.020	-0.016	-0.015	0.014	-0.069	-0.010	0.021
	(0.011)	(0.012)	(0.027)	(0.022)	(0.025)	(0.026)	(0.025)	(0.029)	(0.047)	(0.010)	(0.064)
Jul Precip	0.003	0.087***	0.008	0.011	-0.015	0.007	0.045	0.025	-0.029	-0.011	0.123**
	(0.009)	(0.016)	(0.036)	(0.021)	(0.036)	(0.023)	(0.034)	(0.041)	(0.060)	(0.017)	(0.058)
NDP:Comp	-0.138*	0.596***				0.647*		0.342***			
	(0.082)	(0.108)				(0.351)		(0.112)			
PC:Comp	0.019		-0.729	0.264	-0.007	0.014		0.236**	-0.181	0.032	0.122
	(0.074)		(0.519)	(0.253)	(0.148)	(0.178)		(0.110)	(0.129)	(0.062)	(0.201)
PQ:Comp	-0.410						0.045				
	(0.496)						(0.109)				
SP:Comp	-0.152			-0.060							
	(0.365)			(0.102)							
NDP:Scale	0.039							-1.266*			
	(0.134)							(0.742)			
PC:Scale	-0.121		-0.156					0.149		0.239**	-0.046
	(0.129)		(0.419)					(0.178)		(0.118)	(0.365)
PQ:Scale	-0.608										
	(0.444)										
SP:Scale	-0.141										
	(0.312)										
NDP:Tech	-0.051	0.229***				-0.106		0.097			
	(0.064)	(0.061)				(1.111)		(0.308)			
PC:Tech	0.020		-0.162		-0.020	0.301		-0.199	-0.758	-0.220**	0.055
	(0.060)		(0.178)		(0.138)	(0.207)		(0.341)	(0.501)	(0.100)	(0.237)
PQ:Tech	0.199						0.165				
	(0.342)						(0.157)				
SP:Tech	-0.024										
	(0.300)										
Constant	2.794***	2.724***	3.308***	4.025***	2.767***	2.794***	2.374***	3.197***	2.430***	2.631***	2.953***
	(0.154)	(0.044)	(0.428)	(0.086)	(0.098)	(0.150)	(0.049)	(0.052)	(0.087)	(0.016)	(0.144)
Observations	294	27	29	30	30	30	28	30	30	30	30
Note:									*p<0.1; **p<0.05; ***p<0.01		

Table 2.4| Effect of significant variables and interaction terms on log-transformed per-capita emissions for selected models as displayed in Figure 2.2. In modeling, Liberal was used as the baseline (reference) party except for the provinces AB, SK and MB which had the New Democratic Party as the baseline (reference) party. Since the continuous variables were standardized to (0, 1) range, the coefficients (effect sizes) are directly comparable. Standard errors are shown in parentheses. The provincial abbreviations are CA (Canada), BC (British Columbia), AB (Alberta), SK (Saskatchewan), MB (Manitoba), ON (Ontario), QC (Québec), NS (Nova Scotia), NL (Newfoundland and Labrador), PE (Prince Edward Island), and NB (New Brunswick).

	Dependent variable:										
	Emissions/capita log (kt CO2eq/person)										
	CA	BC	AB	SK	MB	ON	QC	NS	NL	PE	NB
NDP	0.035^{*}	-0.627^{***}				-0.446^{***}		0.667^{*}			
	(0.021)	(0.061)				(0.130)		(0.394)			
PC	0.021		0.787^{***}	-0.245^{***}		0.107^{***}		-0.082^{**}	0.684^{***}	-0.010	
	(0.013)		(0.296)	(0.023)		(0.018)		(0.037)	(0.102)	(0.008)	
PQ	0.053						-0.035^{**}				
	(0.119)						(0.014)				
SP	0.074			-0.039^{**}							
	(0.122)			(0.016)							
Oil		-0.036^{***}		-0.049^{**}	-0.057^{*}	-0.078^{***}		0.231^{***}	-0.157^{***}		
		(0.009)		(0.022)	(0.032)	(0.022)		(0.044)	(0.055)		
Comp	0.068	0.204^{***}	0.518^{*}	-0.108^{***}	-0.233^{**}	0.650^{***}	0.098^{***}	-0.186^{***}	0.156^{**}		0.420^{***}
	(0.056)	(0.026)	(0.308)	(0.036)	(0.098)	(0.096)	(0.032)	(0.050)	(0.061)		(0.143)
Tech	-0.609^{***}	0.017	0.036		0.450^{***}	0.264^{**}	0.183^{***}	-0.563^{***}	0.844^{***}	-0.233^{***}	0.137
	(0.053)	(0.080)	(0.064)		(0.095)	(0.133)	(0.052)	(0.068)	(0.101)	(0.025)	(0.301)
Scale	1.219^{***}		0.296^{***}	0.646^{***}				0.554^{***}		0.209^{***}	1.056^{***}
	(0.188)		(0.041)	(0.066)				(0.074)		(0.021)	(0.174)
$Comp^2$		-0.260^{***}			0.191^{**}	-0.477^{***}					-0.352^{**}
		(0.037)			(0.082)	(0.108)					(0.162)
$Tech^2$		-0.283^{***}	-0.174^{***}		-0.397^{***}	-0.618^{***}	-0.353^{***}			-0.248^{***}	-0.618^{***}
		(0.056)	(0.059)		(0.067)	(0.098)	(0.056)			(0.025)	(0.200)
$Scale^2$	-0.356^{***}			-0.284^{***}				-0.486^{***}			-0.764^{***}
	(0.129)			(0.072)				(0.096)			(0.207)
Ann Temp					-0.069^{***}				-0.116^{***}		
					(0.027)				(0.038)		
Jan Temp	0.022^{**}	0.047^{***}		-0.034^{**}						0.035^{***}	
	(0.011)	(0.011)		(0.016)						(0.004)	

Jul Temp				0.052**	0.071***				0.142***	0.023***	
				(0.023)	(0.027)				(0.047)	(0.003)	
Ann Precip		-0.028**	0.081***					-0.029**			
		(0.011)	(0.024)					(0.014)			
Jan Precip	-0.018*	-0.060***									
	(0.010)	(0.007)									
Jul Precip		0.089***									0.076**
		(0.008)									(0.034)
NDP:Comp	-0.088*	0.673***				0.454***		0.262***			
	(0.047)	(0.062)				(0.141)		(0.076)			
PC:Comp	-0.076*		-0.821***			-0.268***		0.158**	-0.233***		
	(0.039)		(0.314)			(0.046)		(0.065)	(0.073)		
PQ:Comp	-0.091										
	(0.200)										
SP:Comp	-0.254										
	(0.288)										
NDP:Tech		0.256***									
		(0.040)									
PC:Tech									-0.922***	-0.252***	
									(0.137)	(0.067)	
NDP:Scale								-0.964*			
								(0.502)			
PC:Scale								0.107**		0.270***	
								(0.042)		(0.050)	
Constant	2.792***	2.735***	3.389***	3.993***	2.828***	2.678***	2.403***	3.168***	2.483***	2.623***	2.864***
	(0.153)	(0.031)	(0.308)	(0.024)	(0.015)	(0.056)	(0.024)	(0.032)	(0.078)	(0.002)	(0.061)
Observations	294	27	29	30	30	30	28	30	30	30	30

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

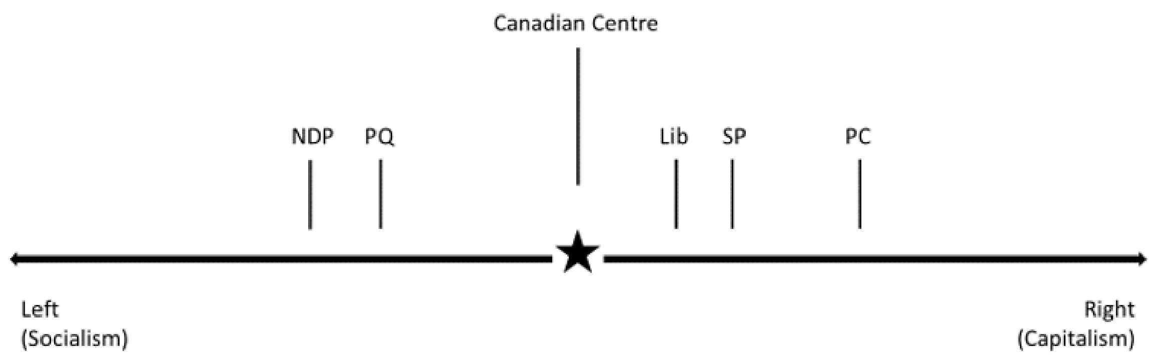


Figure 2.5| The general political spectrum of provincial political parties in Canada. Note that not all parties are in every province. The relative placement of parties on the spectrum is adapted in part from the 2005 Canadian political compass (The Political Compass, 2019). The political parties from left to right are New Democratic Party (NDP), Parti Québécois (PC), Liberal (Lib), Saskatchewan Party (SP), and Progressive Conservative (PC). The placement on the spectrum may vary within each province and across elections. Note that the position of each party on the spectrum is at a relative scale within each province – it means that a "left" party in a province could be regarded as a "right" party in another province, but their relative positions on the spectrum do not change. Our study did not compare the political spectrum across provinces.

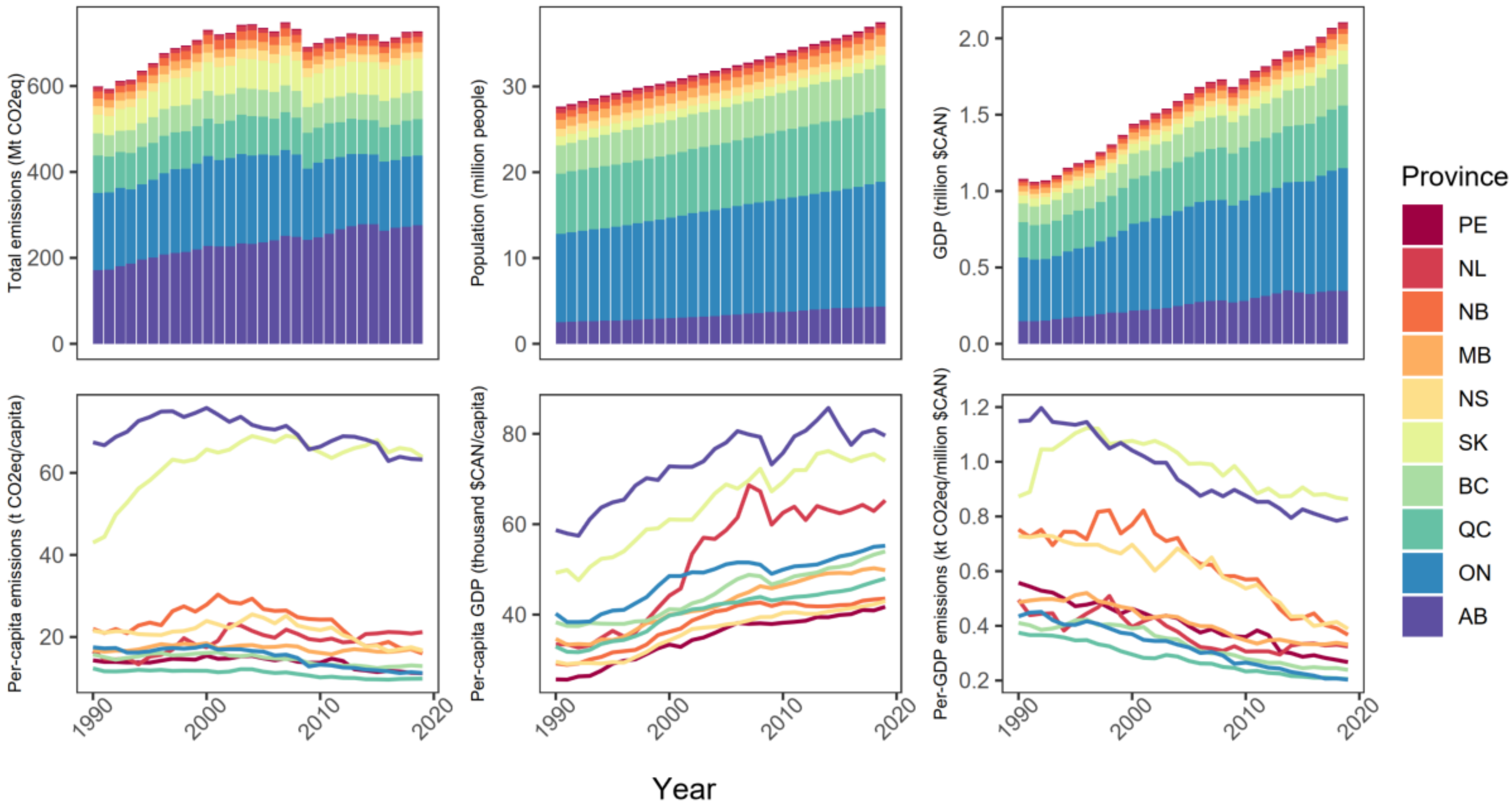


Figure 2.6| Bar and line graphs showing the temporal change of the economic and demographic variables that were used to calculate the dependent variable (per-capita GHG emissions) and socioeconomic variables (independent variables) in the main text. Shown above are total CO_2eq emissions, total population, GDP, per-capita CO_2eq emissions, per-capita GDP, and CO_2eq emissions per GDP for the Canadian provinces from 1990 to 2019. The provincial abbreviations are PE (Prince Edward

Island), NL (Newfoundland and Labrador), NB (New Brunswick), MB (Manitoba), NS (Nova Scotia), SK (Saskatchewan), BC (British Columbia), QC (Québec), AB (Alberta), and ON (Ontario).

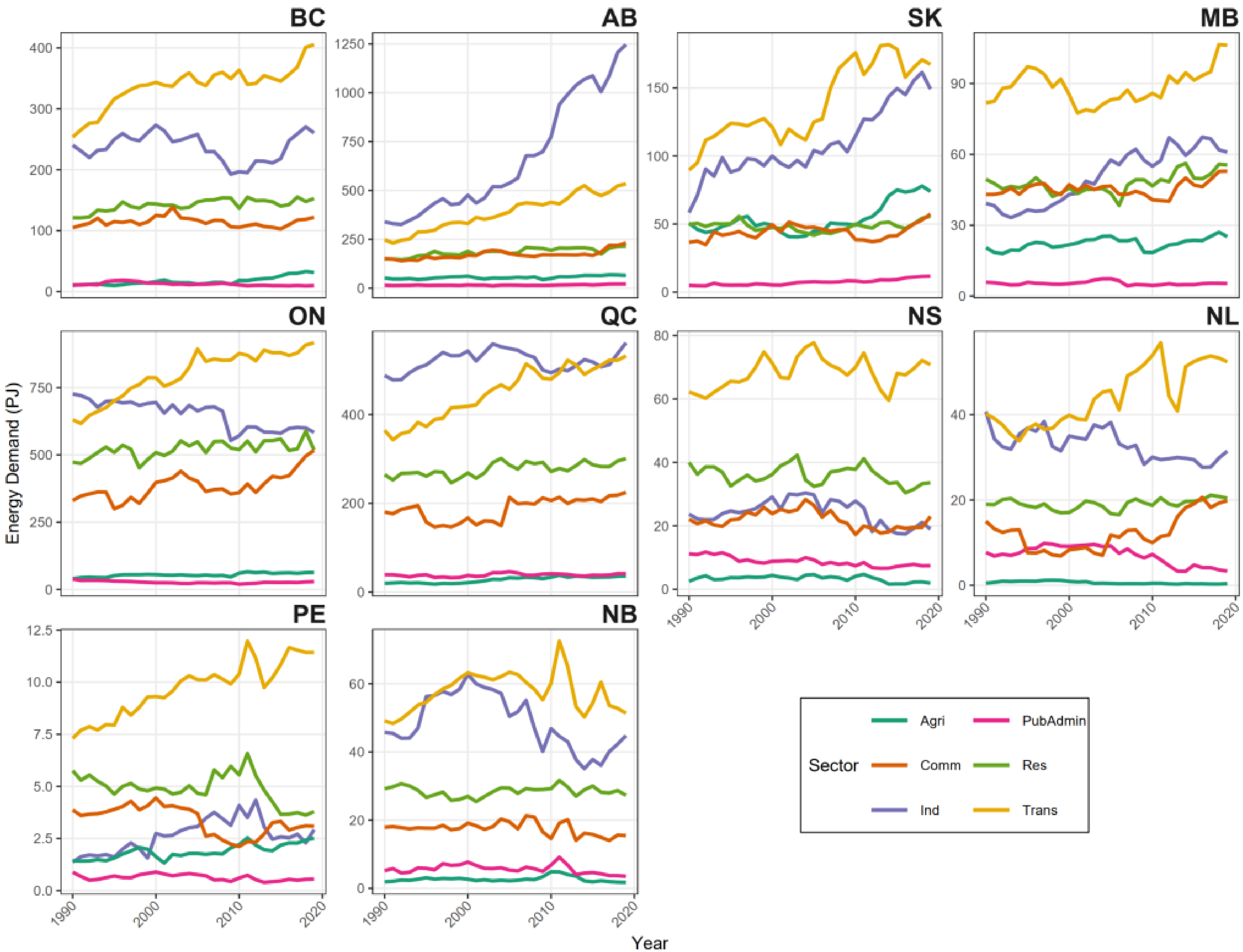

BC
AB
SK
MB
ON
QC
NS
NL
PE
NB
Energy Demand (PJ)
Year
Sector
Agri
PubAdmin
Comm
Res
Ind
Trans

Figure 2.7| Line graphs showing provincial energy demand per societal sector in terajoules (TJ) for each province from 1990 to 2019. Energy values are used to calculate the composition (industrial energy demand to total energy demand ratio) and technological adaptation (GDP per unit of total energy demand) variables in the main text. The six sectors are agriculture (Agri), commercial (Comm), industry (Ind), public administration (PubAdmin), residential (Res) and transportation (Trans). See Figure 2.6 for the provincial abbreviations.

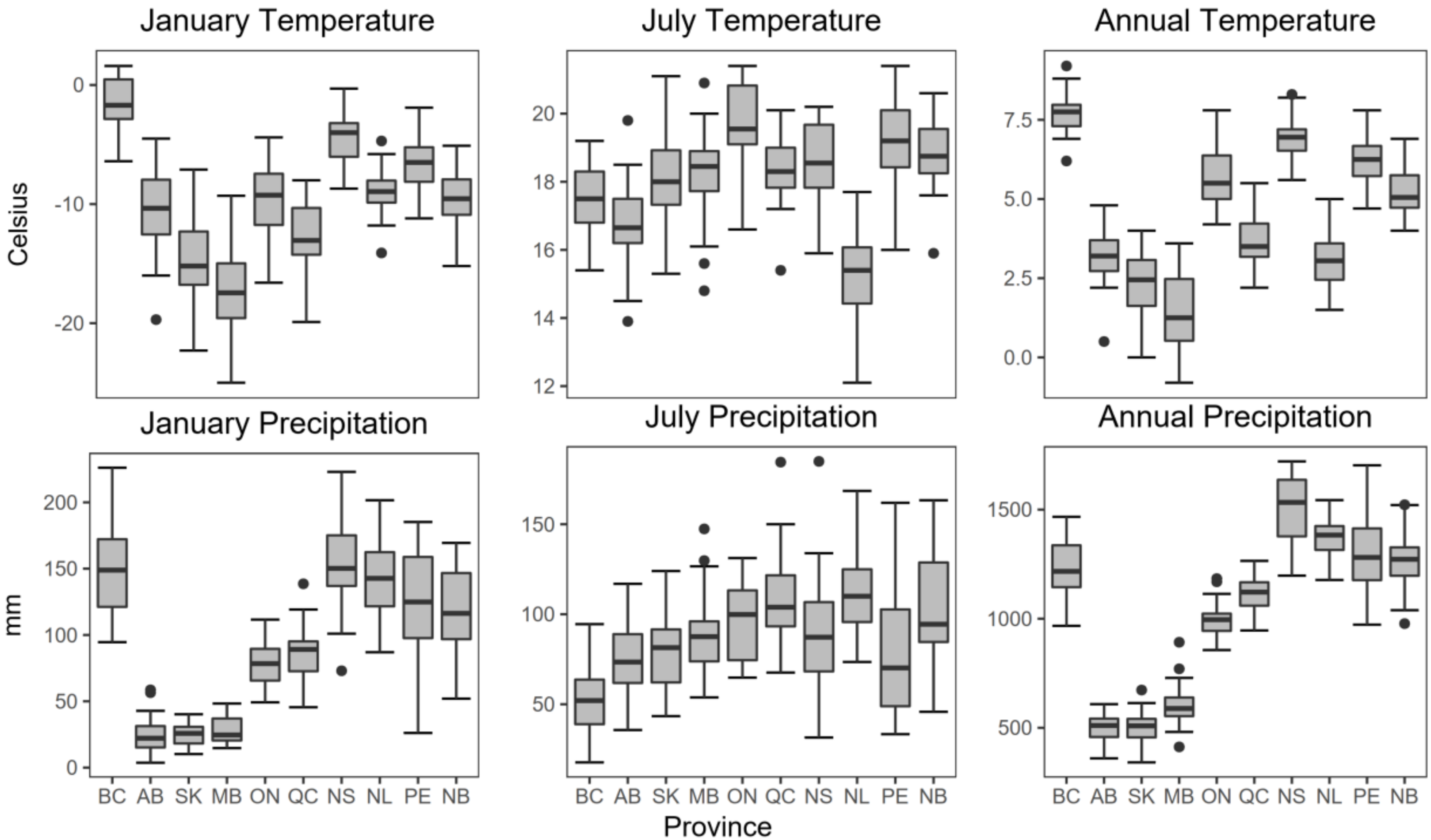


Figure 2.8| Box plots showing the range of weather factors used in this study for each province from 1990 to 2019. The values are averaged across each province for each year from 1990 to 2019. The top row is average temperature in Celsius. The bottom row is an average of total precipitation in millimetres. See Figure 2.6 for the provincial abbreviations.

Chapter Three: Effects of political governance, socioeconomics, and weather on residential GHG emissions across subnational jurisdictions - The case of Canada

3.1 Abstract

Quantification of greenhouse gas emission variation across different jurisdictions is necessary for developing emission reduction policies. We addressed this issue by modelling the effects of political governance, socioeconomics, and weather on household GHGs from electricity, natural gas, and petrol for Canadian city and province jurisdictions from 1997 to 2009. Our models explained 60.6% to 98.3% of the GHG variation for cities and 71.1% to 99.3% for provinces. We further showed socioeconomics was the most important variable, accounting for 15.6% to 49.0% of emission variation in cities and 66.6% to 75.2% in provinces. Political governance was only significant at the city level, contributing at most 4.8% to the variation, but had joint contributions with other variables, particularly socioeconomics. Overall, the drivers of household GHG emissions changed across jurisdictions and energy sources, stressing the importance of integrating local, source specific policies into subnational and national based strategies for effective emission reductions.

3.2 Introduction

Humanity must drastically decrease the emission of anthropogenic greenhouse gases (GHG) across the globe if it is going to avoid the most severe adverse effects of a changing climate (Rockström *et al.*, 2017; Hoegh-Guldberg *et al.*, 2019). Such an unprecedented undertaking requires vertical and horizontal integration of GHG emission policies across governmental jurisdictions, civil society, and businesses (Newell, 2008). Evidence to inform effective integration across jurisdictions remains obscured, inconsistent and underexplored (Adger, Arnell and Tompkins, 2005; Clar, 2019), especially when integrating emission reduction actions at the subnational level with national and international emission targets (UNEP, 2018; Hsu *et al.*, 2019).

An essential prerequisite to integrate subnational emission reductions across jurisdictions is the quantification of the drivers of GHG emissions at the subnational level (Peters, 2010; Bowen and Wittneben, 2011). These emissions can be classified according to the economic sector from which they derive (IPCC, 2014), such as the industrial, commercial, or residential sectors (Natural Resources Canada, 2020). Of the different economic sectors, approximately 72% of total global emissions are attributable to residential emissions from household consumption (Hertwich and Peters, 2009), with household energy consumption alone contributing approximately 21% of total global emissions (UNEP, 2021). Furthermore, residential emissions can be affected by individual and household level choices and behaviours (Dietz *et al.*, 2009), policy interventions and deep decarbonization strategies from governing bodies (Fuso Nerini *et al.*, 2021; Pauliuk *et al.*, 2021), or some amalgamation of both household choices and political interventions (Dubois *et al.*, 2019). Given the breadth of the potential drivers of residential emissions and that individuals and governments alike may affect these emissions, both 'top-down' emission control enforced by governments (Biermann *et al.*, 2012) and 'bottom-up' household and community-based initiatives (van Aalst, Cannon and Burton, 2008; Dietz *et al.*, 2009) may synergistically provide effective residential emission reductions (Cerna, 2013; Conway *et al.*, 2019). This makes further inquiry into the drivers of residential emissions an opportunity to limit global emissions and provide insights into how emission variation changes across subnational jurisdictional boundaries.

Much research on residential GHGs has focused on energy consumption patterns and the underlying emission drivers. They include quantifying the impact of different household energy efficient technologies on energy consumption (Adua *et al.*, 2019), effects of demographic and regional characteristics on energy usage (Glaeser and Kahn, 2010), and that of different policies on household energy usage (Goldstein, Gounaridis and Newell, 2020), amongst other focuses (Geng *et al.*, 2017). Despite these advances, there remains a lack of understanding about how the political governance and socioeconomic drivers of GHGs may affect energy consumption and GHG emissions across different governance jurisdictions (Fuhr, Hickmann and Kern, 2018; Goldstein, Gounaridis and Newell, 2020; Boyce and He, 2022).

To address this lack of understanding, we modelled the effects of political governance, socioeconomics, and weather on household GHG emissions across municipal and provincial jurisdictions in Canada. Canada is responsible for 1.5% of global emissions (Environment and Climate Change Canada, 2021a), with approximately 18.8% of 2017 emissions being attributed to energy use in the residential sector (Statistics Canada, 2019). Quantifying the underlying drivers of these residential GHGs (e.g., governmental sentiment, population density, employment in primary industries, household income, etc.) from different energy sources (i.e., fossil fuel-based electricity, non-fossil fuel-based electricity, natural gas, and petrol) is necessary for understanding the sources of variation in GHG emissions, a requirement for developing informed emission reduction policies. Our results show that the drivers of residential GHG emissions change from the city to provincial jurisdictions, and that the extent of these changes differs from one energy source to another. These findings stress the importance of locally based energy policy actions that are integrated into the larger context of provincial, national, and international based emission reduction strategies. Additionally, these findings help to delineate between meaningful actions that can be taken by citizens to limit personal household emissions with policy actions that require attention from governmental agencies. Furthermore, we highlight the urgency for governing bodies to prioritize the transition of society away from electricity produced by burning fossils fuels to alternative, low emitting sources of electricity production.

3.3 Methods

3.3.1 Data

We modelled annual per-household tonnes of CO_2 equivalent (CO_2eq) GHG emissions from electricity, natural gas, and petrol as a function of political governance, socioeconomic, and weather predictors for 10 census metropolitan areas (CMA; *i.e.*, cities) and eight provinces across Canada from 1997 to 2009 (Figure 3.5, Section 3.7; Tables 3.1 and 3.2, Section 3.7). Following a similar methodology as Fercovic and Gulati (2016), household emissions were estimated using data from the original Surveys of Household Spending (SHS) for each of the study years (Queen's University Library, 2016; Statistics Canada, 2021a). Household spending on electricity, natural gas, and petrol for each year was divided by the price of that energy source to calculate the average number of energy units used per household. The number of energy units were then multiplied by an emissions conversion factor from Environment Canada (2012), providing an estimate of household emissions from each energy source. There were no extensive natural gas distribution systems except for some limited trucking of gas in Nova Scotia, Prince Edward Island, or Newfoundland and Labrador during the timeframe of this study (Statistics Canada, personal communication, July 21, 2020), so natural gas emissions were not calculated for these provinces, or the cities located within these provinces. Additionally, prior to 2004, natural gas was aggregated with other household heating fuels (e.g., wood, heating oils, etc.)

within the SHS, of which approximately 74% of these fuels was natural gas (Fercovic and Gulati, 2016). Given that disaggregated natural gas expenditures were not available for years prior to 2004, and that the majority of household heating fuel use was natural gas, household heating fuel expenditures within the SHS for this timeframe were taken to consist completely of natural gas. Lastly, due to unavailable data in the SHS, Ottawa did not have GHG estimates for 2007 to 2009. These observations were removed.

Political governance data: We obtained historical city council minutes and provincial legislative Hansards (*i.e.*, speeches) from 1997 to 2009 (see Supplementary Information Table 3.1, Section 3.7 for the sources of speeches). Due to unavailable minutes, Toronto did not have political data for 1997 and Ottawa did not have data for 1997 to 2000. These observations were removed. Since a CMA may contain multiple municipalities, only city council minutes from the main urban core, not the satellite municipalities, were used in this study (e.g., only City of Edmonton council minutes were used for the CMA of Edmonton even though this CMA also contains other municipalities such as St. Albert, Sherwood Park, and Spruce Grove). The provinces of Québec and New Brunswick, and CMAs in these two provinces, were excluded from the study due to their Hansards and minutes being predominantly in French or a combination of English and French, respectively.

The minutes and Hansards were converted into textual data (*i.e.*, .txt file extension) using the R software (https://www.r-project.org/) package readtext (Benoit and Obeng, 2021). This textual data was organized by year, spell-checked using the Python (Python Core Team, 2020) port of symspell (Garbe, 2020) and manually, wherever necessary (e.g., ‘corporatestrategyand’ was corrected to ‘corporate strategy and’), and further cleaned (e.g., punctuation, numbers, hyphens, and symbols were removed, etc.) using the R package quanteda (Benoit *et al.*, 2018). Any words that were identified to have multiple spellings (e.g., ‘color’ and ‘colour’) were converted to have uniform spelling across all the textual data.

Given that the minutes/Hansards are organized chronologically, not by subject, an environmental dictionary and a developmental dictionary were created using methods outlined by Deng et al. (2019) to identify sections of the text relevant to this study. Synonyms and antonyms were combined as they both represented the same context in the textual data. For example, the words ‘construction’ and ‘deconstruction’ are both contextually used to describe the preparation and act of constructing buildings, infrastructure, etc. Additionally, some words were identified as belonging to a general category and were grouped as being equivalent under this category. For example, ‘petrol’, ‘diesel’, ‘gasoline’, ‘ethanol’, ‘propane’, etc. were grouped using the term ‘fuel’. Furthermore, words that could pertain to both the environment and development (e.g., ‘water’) were included in only one of the two dictionaries. In these situations, key-words-in-context was utilized to determine which dictionary to enter that given word.

The completed dictionaries were used to identify textual data related to the environment and development using a window of 10 words before and after every instance of each dictionary entry. A window of 10 words was chosen because the average English sentence has approximately 19 words (Cutts, 2013), giving a window that is approximately the length of one average English sentence, maintaining the contextual basis before and after each instance of a word. This rendered 4 political data subsets: city-environmental, city-developmental, province-environmental, and province-developmental.

Annual relative environment and development sentiment scores for both province and city were calculated. This was done by applying a modified version of the Lexicoder Sentiment Dictionary (LSD; Young and Soroka, 2012) to each political data subset discussed above to determine the number of positive and negative sentiments within each subset. The LSD was modified by removing any terms that were included in the environmental and developmental dictionaries because these terms were determined to be discussing environmental and/or developmental processes, not sentiments. For example, 'clean-up' was removed from the LSD as this term was found to mean a literal clean-up of the environment. The environmental and developmental sentiments were then weighted using a ratio of positive to negative sentiments within each data subset, rendering relative weighted sentiment scores for city-environmental, city-developmental, province-environmental, and province-developmental (Figures 3.6 and 3.7, Section 3.7).

An additional political variable that estimates the annual relative placement of each city and each province within a unidimensional policy space was then calculated using the wordfish algorithm (Slapin and Proksch, 2008) within the quanteda package in R (Benoit *et al.*, 2018). To run the wordfish algorithm on the textual data, the environmental and developmental dictionaries were combined. This 'combined' dictionary was used to identify keyword instances of environmental and/or developmental discussions within the city council minutes and the provincial Hansards. All other words were removed, leaving only the dictionary keywords in the minutes/Hansards. The wordfish algorithm was applied to these keywords in the city council minutes and then the provincial Hansards, producing the policy positioning for cities and provinces on a unidimensional environmental-developmental policy spectrum (Figure 3.8, Section 3.7). Following recommendations to interpret the policy spectrum by Vignoli (2019), the wordfish beta values for the words in the analyses were ordered from lowest to highest values. The words associated with the bottom and top 10% of beta values were reclassified as being either 'environmental' or 'developmental' relative to which dictionary they came from before being added to the 'combined' dictionary. A ratio of environmental to developmental words was taken for each end of the spectrum. The highest ratio of environmental to developmental words was interpreted as the environmental end of the unidimensional policy spectrum and vice versa for the developmental end of the spectrum.

Two alternative dictionaries (*i.e.*, one environmental and one developmental) were created by an environmental scientist not directly involved in this study. When comparing the dictionaries, there were some differences between the alternative dictionaries and the dictionaries used in this study, as expected given the subjectivity of dictionary creation. Using these alternative dictionaries, the political variables were recalculated and applied to the regression models described below. Descriptions of the textual analysis methods and a comparison of results using the alternative political variables are detailed in the Supplementary Information.

Household socioeconomic data: The prices of residential electricity ($/kWh) were obtained from Hydro-Québec (2021) and were only reported for select cities within each province. Using the data of those cities, an average weighted by the population share of those cities was calculated to determine the average residential prices of electricity for each province. The provincial monthly prices of residential natural gas ($\$/m^3$) were obtained from Statistics Canada (2021a) and averaged per annum to give average annual prices. City prices of residential natural gas were not available, so the provincial prices from which a city was located were used for that city. The city monthly prices of petrol ($/L) were obtained from Statistics Canada (2021a) and averaged per annum to give average annual prices. Using the data of available cities, an average weighted by population was calculated to determine the average prices of petrol for each province. To account for inflation, Consumer Price Induces (CPI) obtained from Statistics Canada (2021a) were used to convert energy prices into 2002 dollars (Figure 3.9, Section 3.7).

Population density was calculated by dividing population by the 2006 census boundaries area for both cities and provinces (Statistics Canada, 2021a), and then the natural log of these values was used in the analyses. Our measure of job occupation is the ratio of people employed in primary industry to total people employed (Statistics Canada, 2021a). Average household income and average expenditure on education were obtained from the SHS (Queen's University Library, 2016; Statistics Canada, 2021a) and adjusted to 2002 dollars using CPI to account for inflation (Figure 3.10, Section 3.7). Additionally, average number of people per household, average number of rooms per household, household expenditure on education, and the percent of households with two or more vehicles were all obtained from the SHS database (Figures 3.11 and 3.12, Section 3.7; Queen's University Library, 2016; Statistics Canada, 2021a).

Weather data: Climatic data was obtained from Environment and Climate Change Canada (2022a) and used to calculate mean annual temperature and precipitation for each city and province (Figure 3.13, Section 3.7). City values were taken from the weather station within the main urban centre of the CMA (e.g., City of Edmonton for the CMA of Edmonton). Some city precipitation values were missing. In this case, surrogate CMA precipitation values were obtained using the closest weather station to the main urban centre within each CMA (Environment and Climate Change Canada, 2021b). Provincial weather values were averaged across all weather stations within each province to get the provincial average.

3.3.2 Statistical analysis

Per-household GHG emissions from natural gas, petrol, and electricity were modeled for city and provincial jurisdictions, respectively. Before analyzing the data, the numerical independent variables were normalized to a (0, 1) range using $(x - x_{min})/(x_{max} - x_{min})$. Because the mean emissions from electricity produced primarily from fossil fuels was 15.5 times higher than that from non-fossils fuels for cities and 20.2 times higher for provinces (Figure 3.1), electricity from fossil fuels and non-fossil fuels were modeled separately. Multicollinearity tests using a $R^2 >$ 0.90 cut-off did not detect collinearity amongst variables. The dependent variable (*i.e.*, per-household GHGs) was modeled with a linear mixed-effects model for each emission source (*i.e.*, natural gas, petrol, electricity produced from fossil fuels, and electricity produced from non-fossil fuels) for both city and provincial jurisdictions with political governance, socioeconomic, and weather factors as independent variables. Whilst checking model adequacy, heteroscedasticity and/or temporal autocorrelation in model residuals were detected in some emission sources for both city and provincial jurisdictions. We thus proposed the following generalized least squares linear mixed-effects model that included a variance structure to address inhomogeneous variance and a first-order autoregressive term to address temporal autocorrelation.

$$y_i = \beta_0 + \beta_1 wordfish_i + \beta_2 envsent_i + \beta_3 devsent_i + \beta_4 price_i + \beta_5 logdensity_i + \beta_6 price_i + \beta_7 employ_i + \beta_8 income_i + \beta_9 hhsize_i + \beta_{10} avgnumrooms_i + \beta_{11} educ_i + \beta_{12} anntemp_i + \varphi Y_{i-1} + b_i + \varepsilon_i \qquad (3.1)$$

where y_i is per-household GHG emissions produced from either natural gas, petrol, electricity produced from fossil fuels, or electricity from non-fossil fuels; *i* indicates the years from 1997, 1998, …, to 2009, respectively. ϕ is the first-order autoregressive coefficient. b is a random effect representing '*province*' for the provincial jurisdiction models, and '*city*' nested within '*province*' for the city jurisdiction models, except for the non-fossil fuel city model which was a better fit (as assessed by AIC values) with only '*province'* as the random term. There were 8 models in total to estimate (*i.e.*, per-household emissions from four energy sources at city and provincial levels). The petrol models included two additional variables (*i.e.*, number of households with two or more vehicles and annual precipitation) and had the variable for average number of rooms per household removed. The variance structures for models that did not have normally distributed residuals ε_i are provided in Table 3.3 (Section 3.7). Since the numeric independent variables have been normalized to a (0, 1) range, the effect of each independent variable on GHG emissions can be compared directly using the coefficients' βs (effect size) in each model.

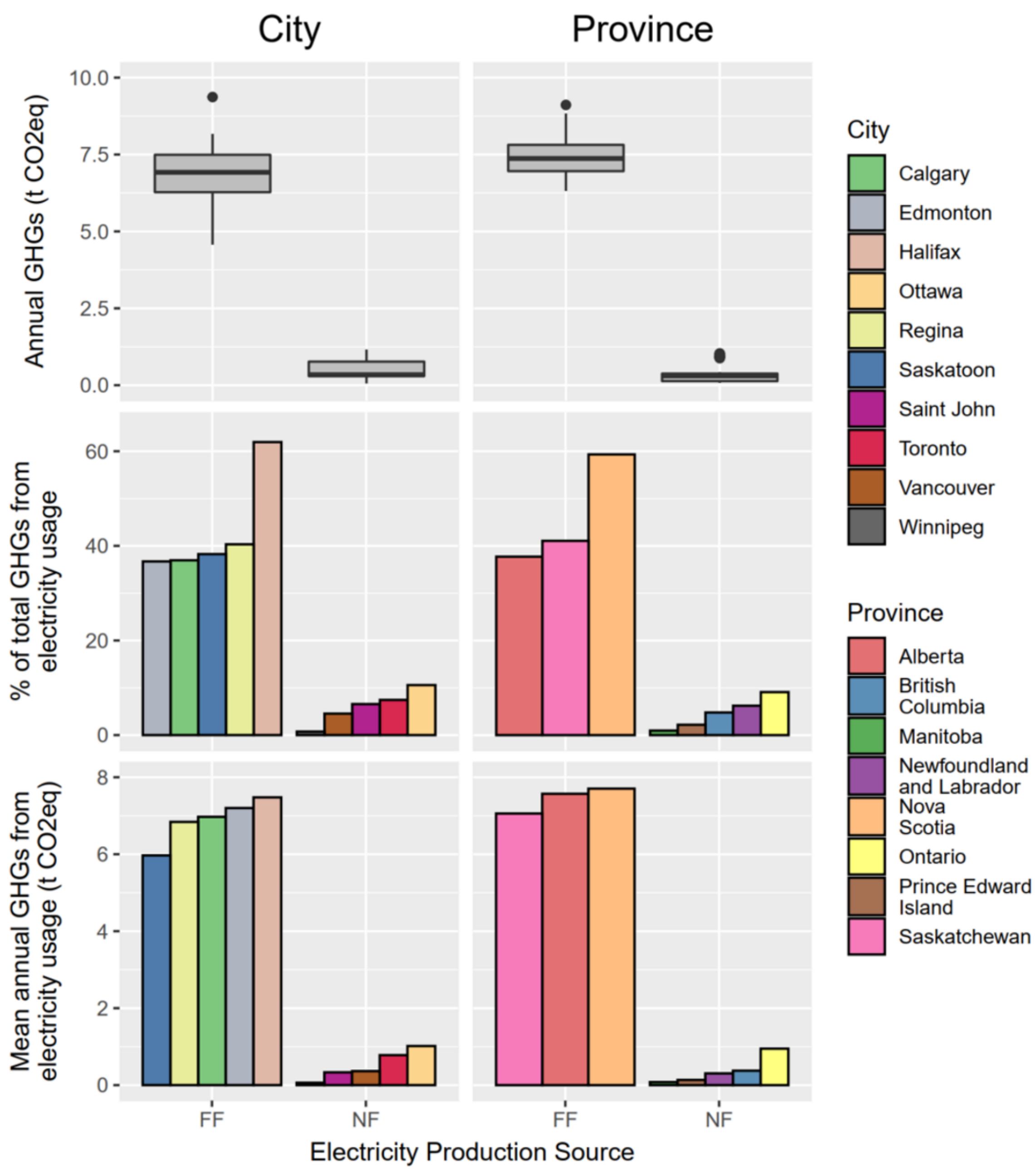


Figure 3.1| Variation in annual emissions from electricity use (top row), percentage of total emissions from electricity usage (middle row) and mean annual emissions (bottom row) per household for cities (left column) and provinces (right column) for the years 1997 to 2009. The electricity production source labelled "FF" are cities/provinces that use electricity produced from fossil fuel sources, while "NF" are cities/provinces that use electricity produced from non-fossil fuel sources. These plots show the drastic difference in emissions from electricity produced from fossil fuels vs emissions from electricity produced from non-fossil fuels sources.

A backward selection process was performed to select the "best" model for each of the eight energy source/jurisdiction models. With each selected model, we implemented variation partitioning, as described by Legendre (2008), to quantify the contributions of political governance, socioeconomics, and weather to GHG emissions. All statistical modelling was performed using R software. The generalized least squares linear mixed-effects model (3.1) was conducted using the gls function in the R package 'nlme' (Pinheiro J, Bates D, DebRoy S, 2017) and variation partitioning was conducted using the R package 'vegan' (Oksanen *et al.*, 2018).

3.4 Results

Annual tonnes of household emissions from electricity, natural gas and petrol varied considerably among cities and provinces (Figure 3.2), with Edmonton contributing most total GHG emissions per household (mean = 19.6 tonnes) at the city level and Alberta at the provincial level (mean = 20.1 tonnes). Per-household GHG emissions generated from the use of the four energy sources at both city and provincial levels were well described using the selected linear mixed-effects models, with R^2 varying from 0.606 to 0.993 (Figure 3.3). However, there is no single set of socioeconomic, political governance or weather variables that can commonly explain the per-household GHG emissions produced from energy uses across the two jurisdiction levels. Despite their differences, the models shared some common results. For example, an increase in energy price consistently affected emissions from the respective energy use, lowering emissions across all jurisdictions and energy sources except for non-fossil fuel electricity at the provincial jurisdiction which increased emissions (Figure 3.3; Table 3.4, Section 3.7). This indicates that energy price was the most important factor impacting GHGs across jurisdictions and energy sources.

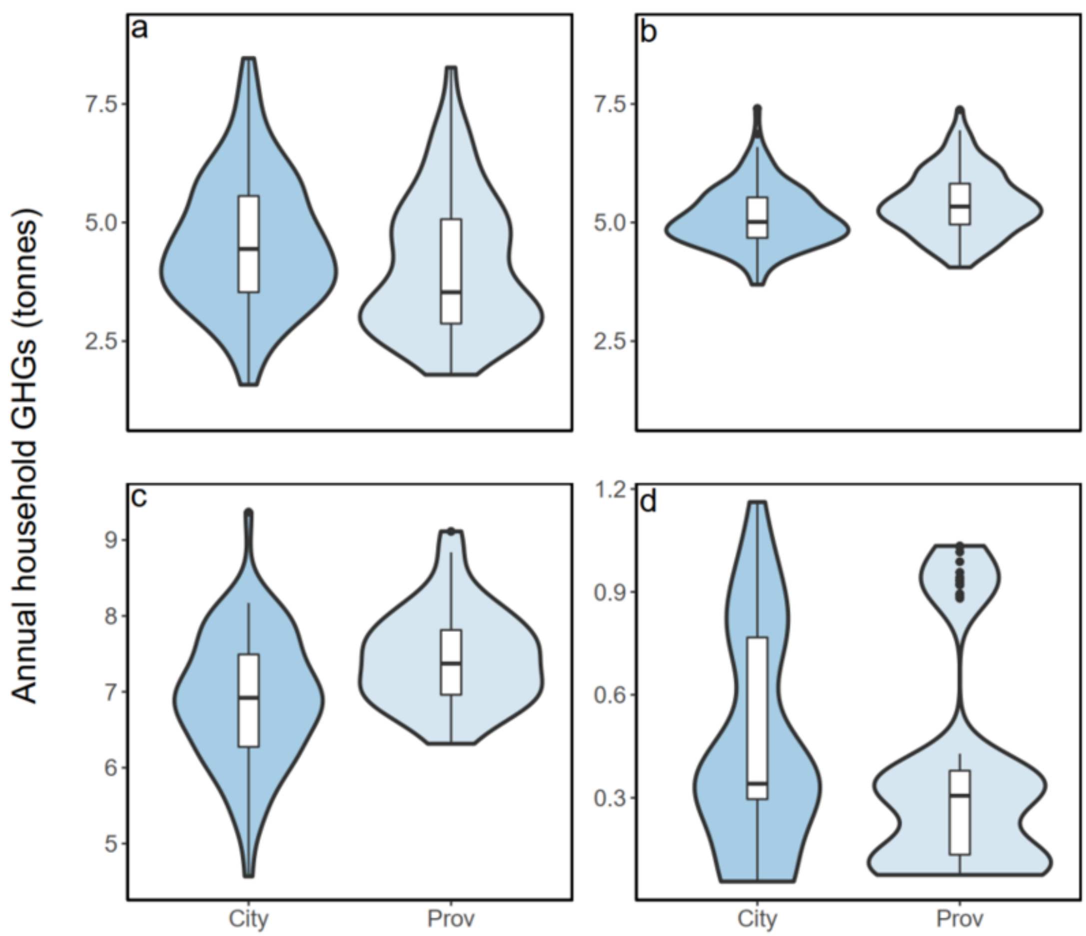


Figure 3.2| Violin plots showing the distribution of annual household GHG emissions for cities (dark blue) and provinces (light blue) from 1997 to 2009. The four panels show the four energy sources: (a) natural gas, (b) petrol, (c) electricity produced from fossil fuels, and (d) electricity produced from non-fossil fuels.

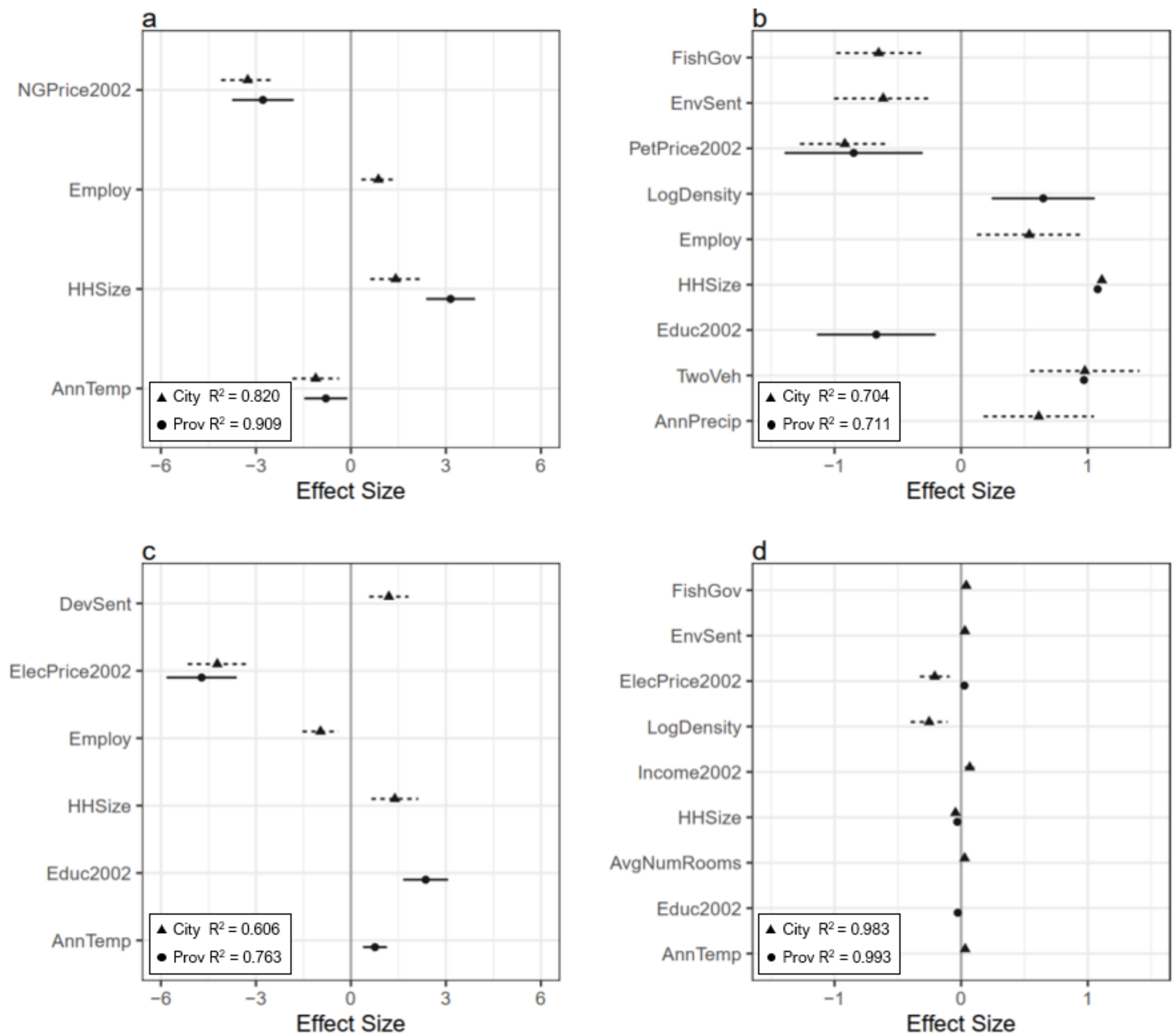


Figure 3.3| Effect sizes and 95% confidence intervals of political governance, socioeconomic, and weather variables on per-household GHG emissions for natural gas use (a), petrol use (b), electricity primarily produced from fossil fuels use (c), and electricity produced from non-fossil fuels use (d). Dashed lines with triangles represent city

jurisdiction models, while solid lines with circles represent provincial jurisdiction models. The adjusted R^2 value for each model (city and province) shows the adequacy of the model. Note that panels on the left column and the right column both have the same effect size scale.

The effects of political governance on household GHG emissions generated by the consumption of the four energy sources, as measured by environmental and developmental political discourse, varied from negative (Figure 3.3b) to positive (Figure 3.3c and 3.3d), and no effect in the case of natural gas (Figure 3.3a). Political governance had effects on GHG emissions produced from petrol and the two sources of electricity at the city level but no effect on emissions from any energy source provincially.

The effects of weather factors were also inconsistent, with mean annual temperature being correlated with lower GHGs from the use of natural gas (Figure 3.3a) but higher emissions from electricity produced from fossil fuel at the provincial level and non-fossil fuel at the city level (Figure 3.3c and 3.3d). Additionally, an increase in mean annual precipitation was associated with increased emissions from the use of petrol at the city level (Figure 3.3b).

The variance partitioning shown in Figure 3.4 indicates that socioeconomic factors contributed the most to per-household GHG emission variation across all four sources of energy use, with the contribution varying from 15.6% to 49.0% on the city level and 66.6% to 99.3% on the provincial level. The weather factors contributed a small percent of variation to the GHG emissions (1.4% - 10.1%) followed by even smaller contributions of governance (0.0% - 4.8%). Both weather and governance factors had joint interactions with socioeconomic factors. For example, 47.6% of emission variation from non-fossil fuel electricity was identified to be a joint interaction between political governance and socioeconomics.

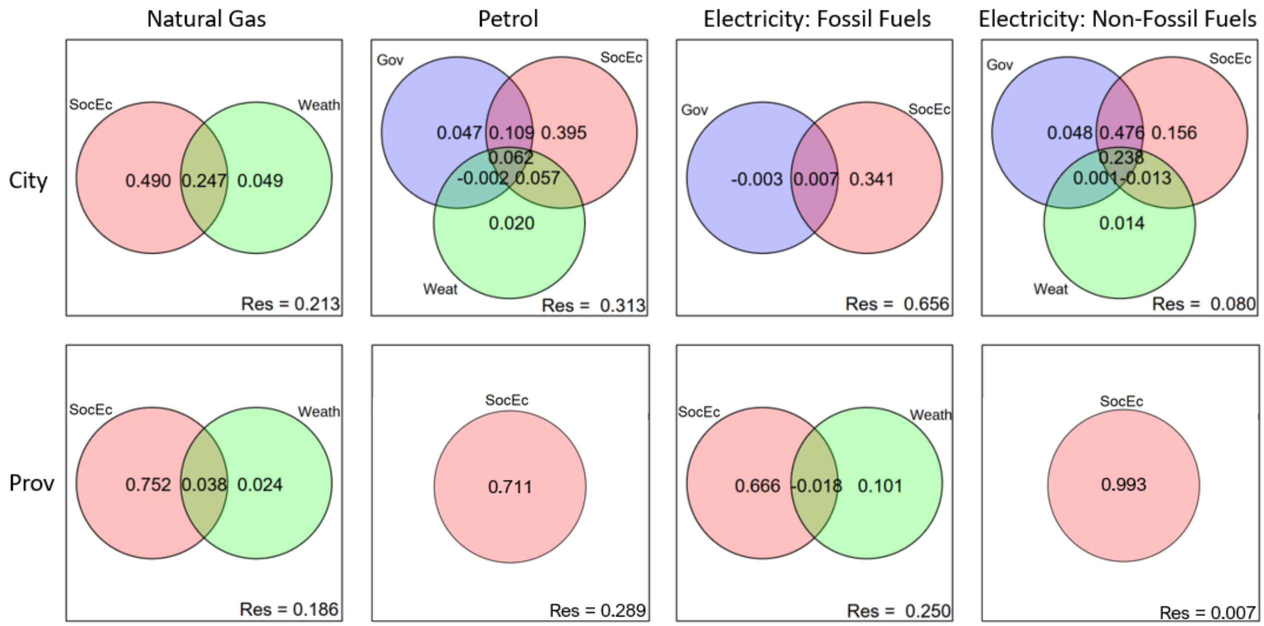


Figure 3.4| Venn diagrams showing the variation partitioning for the contributions of political governance (blue), socioeconomics (red), and weather (green) to per-household GHG emissions from 1997 to 2009 for cities (top row) and provinces (bottom row). The values depict the amount of variation in household emissions from each energy source explained by different variable categories. Circle overlaps indicate joint effects. Negative values are interpreted as zeros (Legendre, 2008). The residual value at the bottom right corner of each diagram denotes the unexplained variation.

3.5 Discussion

Initiatives to protect society and the biosphere from the moderate to severe risks associated with global climate change are failing (IPCC, 2018; Liu and Raftery, 2021). One of the main difficulties in addressing climate change lies in the uncertainties and complexity in the variation of GHG emissions associated with differing levels of political governance within society. The degree to which governance can affect GHG emission variation, from local action to international cooperation, has been much debated (Schreurs, 2008; Lægreid, 2014; Deetman, Hof and van Vuuren, 2015; Dietz *et al.*, 2015; Böhmelt, Böker and Ward, 2016; Martin and Saikawa, 2017; Paterson and P-Laberge, 2018). It is thus imperative that we better understand emission variation across jurisdictions and identify the sources underlying this variation to integrate local emission reduction actions with national and international emission reduction targets (Corfee-Morlot *et al.*, 2009; Fuhr, Hickmann and Kern, 2018; Hsu *et al.*, 2019).

Here, we quantified the effects of socioeconomic, political governance, and weather factors on household GHG emissions across city and provincial jurisdictions in Canada. Our results showed that the drivers of household GHGs changed considerably, in some cases by a large magnitude, from different sources of energy use and different jurisdictions (Figures 3.1–3.4; Table 3.4, Section 3.7). The difference in emissions from electricity produced from fossil fuels versus electricity produced from non-fossil fuels was particularly pronounced, indicating the urgency to shift production of society's electricity from fossil fuels. Our variables representing political governance were shown to affect household emissions for all energy sources except natural gas, but only at the city jurisdictional level. Additionally, the only variable that influenced emissions for all energy sources and across jurisdictions was the price of energy. Interestingly, an increase in price lowered emissions in all instances except for non-fossil fuel electricity at the provincial jurisdictional level, which increased emissions. The mechanisms driving residential emissions change relative to whether those emissions are attributed to the use of natural gas, petrol, or electricity (dependent upon how that electricity was produced). These findings suggest there is no single panacea strategy to reduce GHG emissions and we must be wary of the limitations, or the pros and cons, of applying emission mitigation tools from one sector to another and from one jurisdictional scale to another. Instead, they stress the importance of regionally specific emission mitigation strategies that target identifiable, decomposed sources of residential emissions. These findings also help distinguish between personal actions to limit GHGs that can be applied by the typical household and policy activities that require governmental intervention to effectively limit household emissions.

3.5.1 The socioeconomics of household GHGs

There is much discussion about changing personal behaviours (Nisa *et al.*, 2019) and patterns of consumption (Wiedmann *et al.*, 2020) to address the negative societal and environmental impacts of climate change. Adapting policies which promote changes in human behaviour have been shown to affect emission variation (Dietz *et al.*, 2009; Adua *et al.*, 2019), but this rhetoric has left many people who have made meaningful changes in their lives feeling disempowered and helpless (Cianconi, Betrò and Janiri, 2020), as the impacts of a changing climate continue to worsen despite their actions (Hoegh-Guldberg *et al.*, 2019). Some behaviours and consumptive innovations that were once thought to be effective in lowering household emissions have been shown to be either limited in their effect (Nisa *et al.*, 2019) or produce more emissions than the alternatives they replaced (Adua *et al.*, 2019). For example, there has been much interest in recent years promoting carbon taxes or similar market-based policies to account for the negative externalities in the prices of GHG emitting energy sources (Stiglitz *et al.*, 2017; Tvinnereim and Mehling, 2018; Green, 2021). Our findings suggest that this could be a possible policy tool to lower household GHGs given the fact that increasing energy prices commonly lower emissions (Figure 3.3; Table 3.4, Section 3.7). However, market-based policies, as we pointed out above, should not be used as a panacea policy strategy for all emission sources in all circumstances (Tvinnereim and Mehling, 2018). Increasing the price of electricity from non-fossil fuel sources is correlated with lower emissions for city jurisdictions but higher emissions for provincial jurisdictions, exemplifying a situation where market-based policies may not have the intended consequences and using such policies should be approached with caution. Additionally, using energy prices to leverage the reduction of GHG emissions could be a double-edged sword because it could escalate inflation as we see today.

3.5.2 Political governance and household emissions

Our study helps to unravel where personal household action is inhibited by larger societal concerns that must be addressed by governmental organizations. The clearest case of this is the difference between emissions from electricity produced from fossil fuels vs electricity produced from non-fossil fuels (Figure 3.3c and 3.3d; Table 3.4, Section 3.7), demonstrated by Alberta's coal-based production of electricity emitting over 140 times more GHGs per kWh than Manitoba's hydropower electricity during the timeframe of this study (Environment Canada, 2012). Fossil-fuel based electricity emissions were shown to be affected by municipal governance, increasing in cities which had a more positive developmental sentiment. Given that the population base of provinces lies in cities, this suggests that higher developmental sentiment in city municipalities may reflect stronger local support for fossil fuel development and the use of fossil fuels for electricity production.

Alternatively, household emissions from non-fossil fuel-based electricity were correlated with governmental variables for the city jurisdiction, but the results were counter intuitive. Both a governmental policy position that is more environmental and an increase in environmental sentiment were correlated with an increase in GHG emissions (Figure 3.3d; Table 3.4, Section 3.7). However, these findings make sense if we consider that one of the primary sources of electricity in these provinces is hydropower (Statistics Canada, 2021b). The construction and maintenance of dams to produce hydroelectricity is often highly controversial (Tullos, Tilt and Liermann, 2009). The dams have many environmental and social impacts such as the displacement of people, flora and fauna; substantial land use changes; adverse effects on water quality; as well as many other concerns (Moran *et al.*, 2018; Almeida *et al.*, 2019; Bradford, 2020). Thus, positive environmental discourse may oppose or slow the development and operation of dams, leaving the interim production of electricity to sources that have higher emissions. A reduction in emissions from electricity would be observed upon the completion of these developments because of the low GHG emission footprint of most hydropower projects relative to other electricity sources (Schlömer *et al.*, 2014). The observation that it is political governance at the municipal level that predicted emission variation for both fossil fuel and non-fossil fuel electricity sources stresses the importance of strategically integrating local electricity emission reduction strategies with provincial and national emission reduction policies.

Municipalities are also in a unique position to create local, transportation-focused policies which greatly reduce direct and upstream emissions from vehicle use (Pichler et al., 2017). Our results show that petrol emissions decreased in cities that were on the environmental end of the policy spectrum and had positive environmental sentiments. This suggests that municipal governments that have a more positive environmental rhetoric may be more effective at introducing local initiatives to reduce pollution from vehicles. Such initiatives may include congestion taxes, investing in urban walkability and cycling, increased availability of public transit, pollution control mechanisms and/or vehicle efficiency standards, or education initiatives like those targeted to reduce vehicle idling (Natural Resources Canada, 2016; Pichler *et al.*, 2017; Winkler *et al.*, 2018; Hansson *et al.*, 2019).

3.5.3 Weather variation and household emissions

Variability in weather affects both the production and consumption of energy (Schaeffer *et al.*, 2012). Our results show that an increase in annual temperature is associated with a decrease in GHGs from natural gas for both cities and provinces (Figure 3.3a), an expected finding considering that natural gas is commonly used to heat homes in many regions across Canada. However, an increase in annual temperature was associated with increased emissions from fossil fuel electricity at the provincial level and from non-fossil fuels at the city level (Figure 3.3c and 3.3d), likely from increased electricity use from indoor air conditioning during the summer of each year (Randazzo, de Cian and Mistry, 2020). Additionally, an increase in annual precipitation is correlated with increased urban emissions from petrol, implying that precipitation, including snowfall, increases vehicle use through increased congestion and travel times (Koetse and Rietveld, 2009). Thus, municipalities allocating additional resources to more efficient snow removal procedures could lower drive times and collisions (Liu *et al.*, 2014; Saha *et al.*, 2016), and potentially limit vehicular emissions in the process.

3.5.4 Overall implications for household emissions

Our study shows that the drivers of household GHGs change across energy sources and jurisdictional levels, emphasizing the importance of regionally specific, source dependent policy strategies. The roles of institutions and individuals to limit household emissions must be clearly defined (Dubois *et al.*, 2019). This includes better organizing people and resources across horizontal and vertical jurisdictions (Clar, 2019). Some argue for top-down approaches for regulating the actions of individuals and organizations to limit emissions, such as governmental interventions like a carbon tax (Peñasco, Anadón and Verdolini, 2021). Others argue that bottom-up approaches are more effective because they encourage individuals and local organizations to take actions that have visible impacts within their own communities (Dietz *et al.*, 2009; Creutzig *et al.*, 2016). Realistically, top-down and bottom-up approaches have their own strengths and weaknesses (Wiedmann *et al.*, 2020), and both, if managed strategically, complement each other in positioning society to do the necessary work required to adapt to the climate change crisis (IPCC, 2014).

Distinguishing where top-down and/or bottom-up approaches are most effective in adapting to the changing climate and how to best apply these approaches in differing circumstances is essential (Conway *et al.*, 2019). This includes all levels of government providing the necessary support to help municipalities guide and implement local emission reduction initiatives (Kuramochi *et al.*, 2020). Moreover, individual action, such as becoming conscious of one's consumptive patterns, is crucial for successful emission mitigation (Ivanova *et al.*, 2020), but clearly defining the meaningful impacts that individuals play in reducing emissions relative to dominant societal structures outside of the control of individuals is vital for society to confront the growing climate crisis.

3.6 Supplementary information for Chapter Three

3.6.1 Political text mining and wordfish analysis details

Historical city council minutes and provincial legislative Hansards (*i.e.*, speeches) from 1997 to 2009 were used to calculate the political variables (Table 3.1). These documents were converted to textual data using the R software package readtext (Benoit and Obeng, 2021) and organized by year. The textual data were spell checked using the Python (Python Core Team, 2020) port of symspell (Garbe, 2020) in 3kb sections (approx. 1500 words per section). Visual inspection of the texts revealed that most identified spelling errors were corrected. Some spelling mistakes persisted, most of which consisted of missing spaces between two or more words and were located most often in the Calgary city council minutes. Where identified, these mistakes were corrected manually (*e.g.,* 'corporatestrategyand' was corrected to 'corporate strategy and'). However, due to the inability to visually inspect the entirety of the textual data due to the size of the dataset (approx. 1.75GB in .txt format), not all mistakes were detected. Using the R package quanteda (Benoit *et al.*, 2018), further cleaning of the data occurred (*i.e.*, stop words, punctuation, numbers, hyphens, and symbols were removed, etc.). Any words that were identified to have multiple spellings (e.g., 'color' and 'colour') were converted to have uniform spelling across all the textual data.

Following methods outlined by (Deng *et al.*, 2017), two dictionaries were developed: an environmental dictionary and a developmental dictionary. This was done by creating a coarse dictionary of words that related to the environment or development using the city data, followed by words in the provincial data not found in the city data. Words with less than 25 instances throughout the city or provincial data were not included in the rough dictionary. After the coarse dictionary was created (1449 words total), the general context of each word was determined using keywords-in-context. Words with a large proportion of multiple meanings were removed. For example, the word 'woods' could denote a forest but may also denote a place (e.g., Mill Woods), a name (e.g., Michael Woods), or a store (e.g., General Woods Store), etc. Thus, the word 'woods' was removed from the dictionary due to having too many potential contexts. Since synonyms and antonyms can often represent the same context in the textual data (e.g., the words 'deconstruction' and 'construction' both describe the preparation and act of constructing buildings, infrastructure, etc.), these words were combined. Additionally, some words were identified as belonging to a general category and were grouped as being equivalent under this category. For example, 'petrol', 'diesel', 'gasoline', 'ethanol', 'propane', etc. were grouped using the term 'fuel'. The remaining words were then categorized as being either an 'environmental' word or a 'developmental' word. Some words, such as 'water', could be simultaneously classified into both the environmental and developmental categories. However, only one category was chosen for each word, making each word entry unique to one category. For example, 'water' was chosen to be more representative of an environmental word than a developmental word and was added to the environmental dictionary. The remaining words were stemmed and then combined in some instances. For example, 'produce', 'producer', 'produced', etc., all became 'produc*'. This process led to an environmental dictionary containing 64 entrees and a developmental dictionary containing 42 entrees.

The provincial Hansards and city council minutes data were organized annually according to each province/city. Using the dictionaries above, textual data related to the environment and development were identified using a window of 10 words before and after every instance of the words in each dictionary. To maintain the contextual basis before and after each instance of a word, a window of 10 words was chosen because the average English sentence has approximately 19 words (Cutts, 2013). This provided a window that is approximately the length of one average English sentence. Four political data subsets were rendered from this process: city-environmental, city-developmental, province-environmental, and province-developmental.

Relative environment and development sentiment scores were calculated for both province and city using the four data subsets by applying a modified version of the Lexicoder Sentiment Dictionary (LSD; Young and Soroka, 2012). The LSD was modified by removing any terms that were included in the environmental and developmental dictionaries because these terms were determined to be discussing environmental and/or developmental processes, not sentiments. For example, 'clean-up' was removed from the LSD as this term was found to mean a literal clean-up of the environment. The environmental and developmental sentiments were then weighted using a ratio of positive to negative sentiments within each data subset, rendering relative proportionally weighted sentiment scores for city-environmental, city-developmental, province-environmental, and province-developmental (Figures 3.6 and 3.7).

An additional variable that identified the relative placement of each city and province annually on a unidimensional policy spectrum was calculated. Given that our textual data was approximately 1.75GB in txt format, the unsupervised automated wordfish algorithm (Proksch and Slapin, 2009) was chosen to analyze the data because unsupervised methods (*i.e.*, wordfish) become suitable when datasets contain too much data for supervised methods such as manually coding the texts (Ruedin and Morales, 2019). It is recommended that only a subsample of text be used for the wordfish analyses related to the area of policy one would like to explore (Proksch and Slapin, 2009). To do this, the two dictionaries described above were combined to form an overall environmental-development dictionary. This combined dictionary was used to remove all words from the textual data except the words found in this dictionary, leaving only words related to the environmental-developmental policy spectrum within each annual document. The wordfish algorithm was ran on these documents using the quanteda (Benoit *et al.*, 2018) package in R. Following recommendations by Vignoli (2019), the beta values for each word were inspected to interpret the policy spectrum. To determine which side of the policy spectrum was more environmental based and which was more developmental based, the words were sorted from the lowest beta values to the highest. The 10% most negative and positive beta value words were recategorized according to which dictionary they were located. A ratio of environmental to developmental words was taken for both the negative end and positive end of the policy spectrum, and the end which had the highest ratio of environmental words was interpreted as being the environmental end of the spectrum (Figure 3.8).

Two alternative dictionaries (*i.e.*, one environmental and one developmental) were created by an environmental scientist not directly involved in this study following the dictionary creation method used above. The political variables were recalculated using these alternative dictionaries and Wilcoxon signed rank tests were used to compare the values of the political variables from both sets of dictionaries. The Wilcoxon tests showed that the provincial and city wordfish results and the provincial environmental sentiment were not significantly different (p values of 0.2544, 0.7864, and 0.2113, respectively). However, the provincial developmental, city developmental, and city environmental sentiments were significantly different (p values of 0.0005, 0.0016, and $< 2.2e-16$, respectively). This difference is partially due to a disagreement about whether the base words ‘energy’ and ‘industry’, and the suffixed variants of these words (e.g., ‘industrial’), belong to the developmental or environmental dictionaries. These two words and their variants are in the developmental dictionary used in the analyses in this study, while these words are in the alternate environmental dictionary used for comparison. To address this discrepancy across dictionaries, the alternative variables were applied to the selected linear mixed-effects models described in the main text. The results can be viewed in Table 3.5.

3.6.2 Supplementary tables and figures

Table 3.1| Summary of data sources for each variable.

Variable Category	**Variable**	**Data**	**Source**
Dependent	Annual per-household residential emissions from electricity, natural gas, and petrol (kt CO_2eq)	Average expenditure per household, electricity (CAN$)	Surveys of Household Spending, variable 2034 (1997 – 2003), variable 20310 (2004 – 2009), (Statistics Canada, 2021) (*used original surveys available at https://library.queensu.ca/data/shs_tables/)
		Average expenditure per household, natural gas (CAN$)	Surveys of Household Spending, variable 2032 (1997 – 2003), variable 20320 (2004 – 2009), (Statistics Canada, 2021) (*used original surveys available at https://library.queensu.ca/data/shs_tables/)
		Average expenditure per household, petrol (CAN$)	Surveys of Household Spending, variable 3050 (1997 – 2003), variable 30500 (2004 – 2009), (Statistics Canada, 2021) (*used original surveys available at https://library.queensu.ca/data/shs_tables/)
		Average price of residential electricity (CAN¢/kWh)	Comparisons of Electricity Prices in Major North American Cities, 1997 -2009, (Hydro-Québec, 2021)
		Provincial monthly prices of residential natural gas (CAN$/$m^3$)	Table: 25-10-0033-01 (Statistics Canada, 2021)
		Monthly prices of petrol (CAN$/L)	Table: 18-10-0001-01 (Statistics Canada, 2021)

		Consumer Price Index, 2002 CAN$	Table: 18-10-0005-01 (Statistics Canada, 2021)
Political	Environmental sentiment Developmental sentiment Placement on environmental-developmental spectrum	City council minutes	(City of Calgary, 2021), (City of Edmonton, 2021), (Halifax Regional Municipality, 2021), (City of Ottawa, 2021), (City of Regina, 2021), (City of Saskatoon, 2021), (City of St. John's, 2021), (City of Toronto, 2021), (City of Vancouver, 2021), (City of Winnipeg, 2021)
		Provincial legislative Hansards	(Legislative Assembly of Alberta, 2021), (Legislative Assembly of British Columbia, 2021), (Legislative Assembly of Manitoba, 2021), (Newfoundland and Labrador House of Assembly, 2021), (Nova Scotia Assembly, 2021), (Legislative Assembly of Ontario, 2021), (Legislative Assembly of Prince Edward Island, 2021), (Legislative Assembly of Saskatchewan, 2021)
Household socioeconomics	Population Density	Population	Tables: 17-10-0046-01 and 17-10-0052-01, (Statistics Canada, 2021)
		Land area (km^2)	(Statistics Canada, 2019)
	Ratio of people employed in primary industries	CMA Total employed, all occupations	Tables: 14-10-0162-01 and 14-10-0314-01, (Statistics Canada, 2021)
		CMA Occupations unique to primary industry (1997 – 2000)	Table: 14-10-0162-01, (Statistics Canada, 2021)
		CMA Natural resources, agriculture and related production occupations (2001 – 2009)	Table: 14-10-0314-01, (Statistics Canada, 2021)
		Province Total, all occupations	Table: 14-10-0297-01, (Statistics Canada, 2021)
			Table: 14-10-0297-01, (Statistics Canada, 2021)

		Province Natural resources, agriculture and related production occupations	
	Median household income	Household income before tax (CAN$)	Surveys of Household Spending, variable 176 (1997 – 2003), variable 1760 (2004 – 2009), (Statistics Canada, 2021) (*used original surveys available at https://library.queensu.ca/data/shs_tables/)
	Average # of people per household	Household size	Surveys of Household Spending, variable 110 (1997 – 2003), variable 1100 (2004 – 2009), (Statistics Canada, 2021) (*used original surveys available at https://library.queensu.ca/data/shs_tables/)
	Average # of rooms per household	Average number of rooms per dwelling	Surveys of Household Spending, Household Characteristics, (Statistics Canada, 2021) (*used original surveys available at https://library.queensu.ca/data/shs_tables/)
	Average household expenditure on education	Education (CAN$)	Surveys of Household Spending, variable 4400-4470 (1997 – 2003), variable 44000-44700 (2004 – 2009), (Statistics Canada, 2021) (*used original surveys available at https://library.queensu.ca/data/shs_tables/)
	% of households with 2 or more vehicles	Owned vehicles (automobiles, trucks and vans) – 2 or more	Surveys of Household Spending, Household Characteristics, (Statistics Canada, 2021) (*used original surveys available at https://library.queensu.ca/data/shs_tables/)
Weather	Mean annual temperature (°C)	Monthly total of daily adjusted temperature	(Environment and Climate Change Canada, 2017) (see (Vincent *et al.*, 2012, 2015) for homogenizing details)
	Total annual precipitation (mm)	Monthly total of daily adjusted precipitation	(Environment and Climate Change Canada, 2017) (see (Vincent *et al.*, 2012, 2015) for homogenizing details)

Historical data, precipitation	(Environment and Climate Change Canada, 2021)

Table 3.2| Provinces and cities, with their abbreviations, in this study.

Province/City	Abbreviation
Alberta	AB
British Columbia	BC
Manitoba	MB
Newfoundland and Labrador	NL
Nova Scotia	NS
Ontario	ON
Prince Edward Island	PE
Saskatchewan	SK
Calgary	Cal
Edmonton	Edm
Halifax	Hal
Ottawa	Ott
Regina	Reg
Saskatoon	Sas
St. John’s	StJ
Toronto	Tor
Vancouver	Van
Winnipeg	Win

Table 3.3| Variance structures for modeling the inhomogeneous residuals for each of the models presented below. Subscript *j* represents each province where *j* = AB, BC, …, to SK, and *k* represents each city where *k* = Cal, Edm, …, Win, in year *i* = 1997, 1991, …, to 2009, respectively.

Energy Source	Jurisdiction	Error Term Structure
Natural gas	City	$\varepsilon_{ijk} \sim N(0, \sigma_k^2)$
	Province	$\varepsilon_{ij} \sim N(0, \sigma_j^2)$
Petrol	City	$\varepsilon_{ijk} \sim N(0, \sigma^2)$
	Province	$\varepsilon_{ij} \sim N(0, \sigma^2 e^{2\delta \bullet logdensity_i})$
Electricity ~ fossil fuels	City	$\varepsilon_{ijk} \sim N(0, \sigma_k^2)$
	Province	$\varepsilon_{ij} \sim N(0, \sigma^2)$
Electricity ~ non-fossil fuels	City	$\varepsilon_{ijk} \sim N(0, \sigma_j^2)$
	Province	$\varepsilon_{ij} \sim N(0, \sigma_j^2 e^{2\delta_{ij}})$

Table 3.4| The output of the selected mixed-effects models analyzed in this study (visualized in Fig. 3 of the main text). Emissions from electricity were separated into that produced from fossil fuels (FF) and produced from non-fossil fuels (NF). Since the continuous variables were standardized to (0, 1) range, the coefficients are interpreted as effect sizes and are comparable across variables. The asterisks beside each coefficient represent the level of significance as described in the bottom right of the table. Standard errors are shown in parentheses.

	Dependent variable:							
	NatGasGHG		PetroGHG		ElecGHG			
	CityNG	ProvNG	CityPet	ProvPet	CityFF	ProvFF	CityNF	ProvNF
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
FishGov			-0.652*** (0.171)				0.040** (0.013)	
EnvSent			-0.615** (0.198)				0.030** (0.009)	
DevSent					1.198*** (0.316)			
NGPrice2002	-3.259*** (0.429)	-2.780*** (0.496)						
PetPrice2002			-0.919*** (0.181)	-0.849** (0.278)				
ElecPrice2002					-4.221*** (0.476)	-4.715*** (0.565)	-0.208** (0.060)	0.026* (0.012)
LogDensity				0.648** (0.207)			-0.253** (0.074)	
Employ	0.868** (0.274)		0.538* (0.211)		-0.962** (0.291)			
Income2002							0.068** (0.020)	
HHSize	1.415*** (0.410)	3.148*** (0.394)	1.111*** (0.204)	1.078*** (0.240)	1.388*** (0.378)		-0.045** (0.013)	-0.030*** (0.006)
AvgNumRooms							0.028* (0.011)	
Educ2002				-0.670** (0.239)		2.360*** (0.362)		-0.027** (0.008)
TwoVeh			0.977*** (0.220)	0.970** (0.296)				
AnnTemp	-1.112** (0.376)	-0.791* (0.347)				0.759*** (0.193)	0.032** (0.010)	
AnnPrecip			0.613** (0.222)					
Constant	5.862*** (0.324)	5.022*** (0.498)	4.918*** (0.263)	4.746*** (0.332)	8.791*** (0.471)	9.390*** (0.405)	0.552* (0.211)	0.386* (0.158)
Observations	96	65	122	104	65	39	57	65
Note:								*p<0.05; **p<0.01; ***p<0.001

Table 3.5| The output of the selected mixed-effects models analyzed in this study using the political variables estimated using the alternate dictionaries. Emissions from electricity were separated into that produced from fossil fuels (FF) and produced from non-fossil fuels (NF). Since the continuous variables were standardized to (0, 1) range, the coefficients are interpreted as effect sizes. Asterisks beside each coefficient represent the level of significance described in the bottom right of the table. Standard errors are shown in parentheses.

	Dependent variable:							
	NatGasGHG		PetroGHG		ElecGHG			
	CityNG	ProvNG	CityPet	ProvPet	CityFF	ProvFF	CityNF	ProvNF
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
FishGov			-0.228 (0.228)				-0.023 (0.020)	
EnvSent			-0.124 (0.166)				0.008 (0.010)	
DevSent					0.512 (0.360)			
NGPrice2002	-3.259*** (0.429)	-2.780*** (0.496)						
PetPrice2002			-0.961** (0.350)	-0.849** (0.278)				
ElecPrice2002					-3.902*** (0.609)	-4.715*** (0.565)	-0.249** (0.076)	0.026* (0.012)
LogDensity				0.648** (0.207)			-0.258** (0.075)	
Employ	0.868** (0.274)		0.405 (0.234)		-0.952** (0.313)			
Income2002							0.054* (0.025)	
HHSize	1.415*** (0.410)	3.148*** (0.394)	1.190*** (0.230)	1.078*** (0.240)	1.566*** (0.423)		-0.029 (0.015)	-0.030*** (0.006)
AvgNumRooms							0.024 (0.015)	
Educ2002				-0.670** (0.239)		2.360*** (0.362)		-0.027** (0.008)
TwoVeh			0.894** (0.314)	0.970** (0.296)				
AnnTemp	-1.112** (0.376)	-0.791* (0.347)				0.759*** (0.193)	0.015 (0.012)	
AnnPrecip			0.386 (0.324)					
Constant	5.862*** (0.324)	5.022*** (0.498)	4.491*** (0.314)	4.746*** (0.332)	9.002*** (0.575)	9.390*** (0.405)	0.626** (0.214)	0.386* (0.158)
Observations	96	65	122	104	65	39	57	65
Note:								*p<0.05; **p<0.01; ***p<0.001

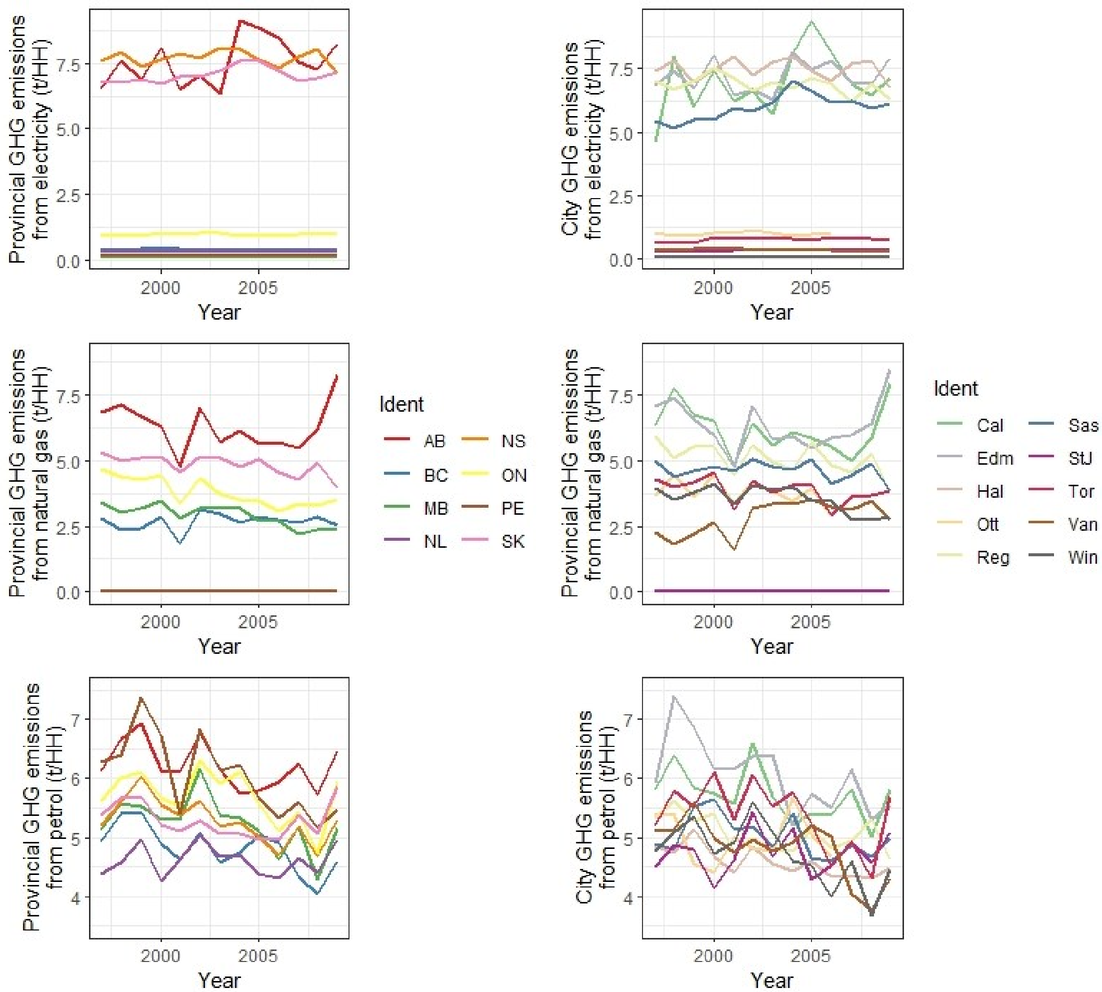


Figure 3.5| Temporal changes of CO_2eq emissions (tonnes/household) for electricity, natural gas, and petrol for provinces (right column) and cities (left column) from 1997 to 2009. These values were calculated by using household expenditure for each energy source, dividing by the price of that energy source to give units consumed per household, and then multiplying that value by a CO_2eq conversion factor for each year, providing an estimate of emissions from each energy source per year. The provinces of Newfoundland and Labrador, Nova Scotia and Prince Edward Island, and the cities within those provinces are shown here to have 0 emissions from natural gas because these provinces had no extensive natural gas distribution systems during the timeframe of this study.

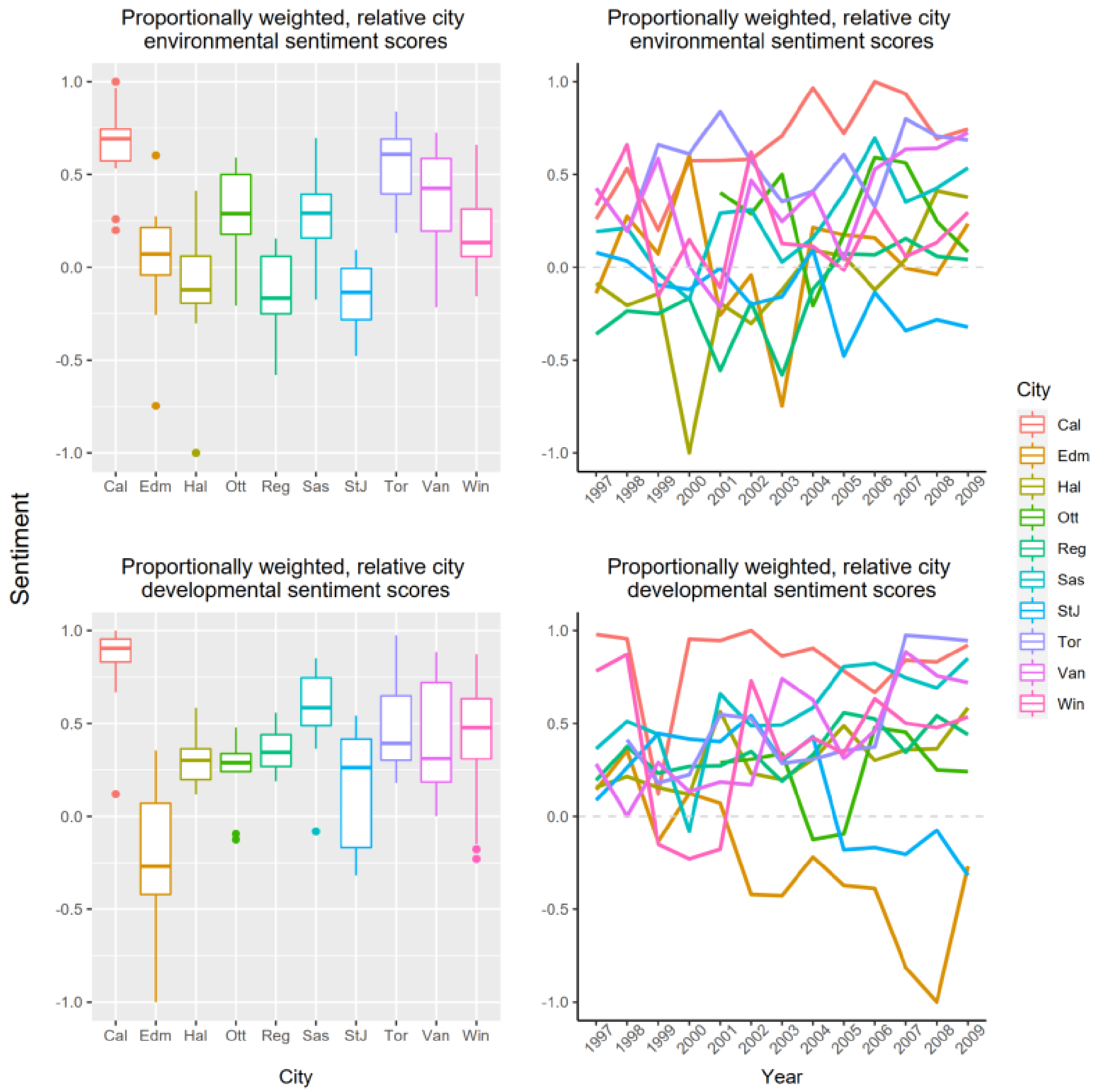


Figure 3.6| Proportionally weighted, relative environmental (top row) and developmental (bottom row) sentiment scores for cities, calculated using city council minutes. The plots have been centred on 0 to visualize the relative placement of each city, so a negative value does not mean that that city has more negative sentiments than positive, but that the negative to positive sentiment ratio is higher relative to the other cities present. The left column visualizes this data using boxplots, while the right column visualizes this data from 1997 to 2009 using a line graph.

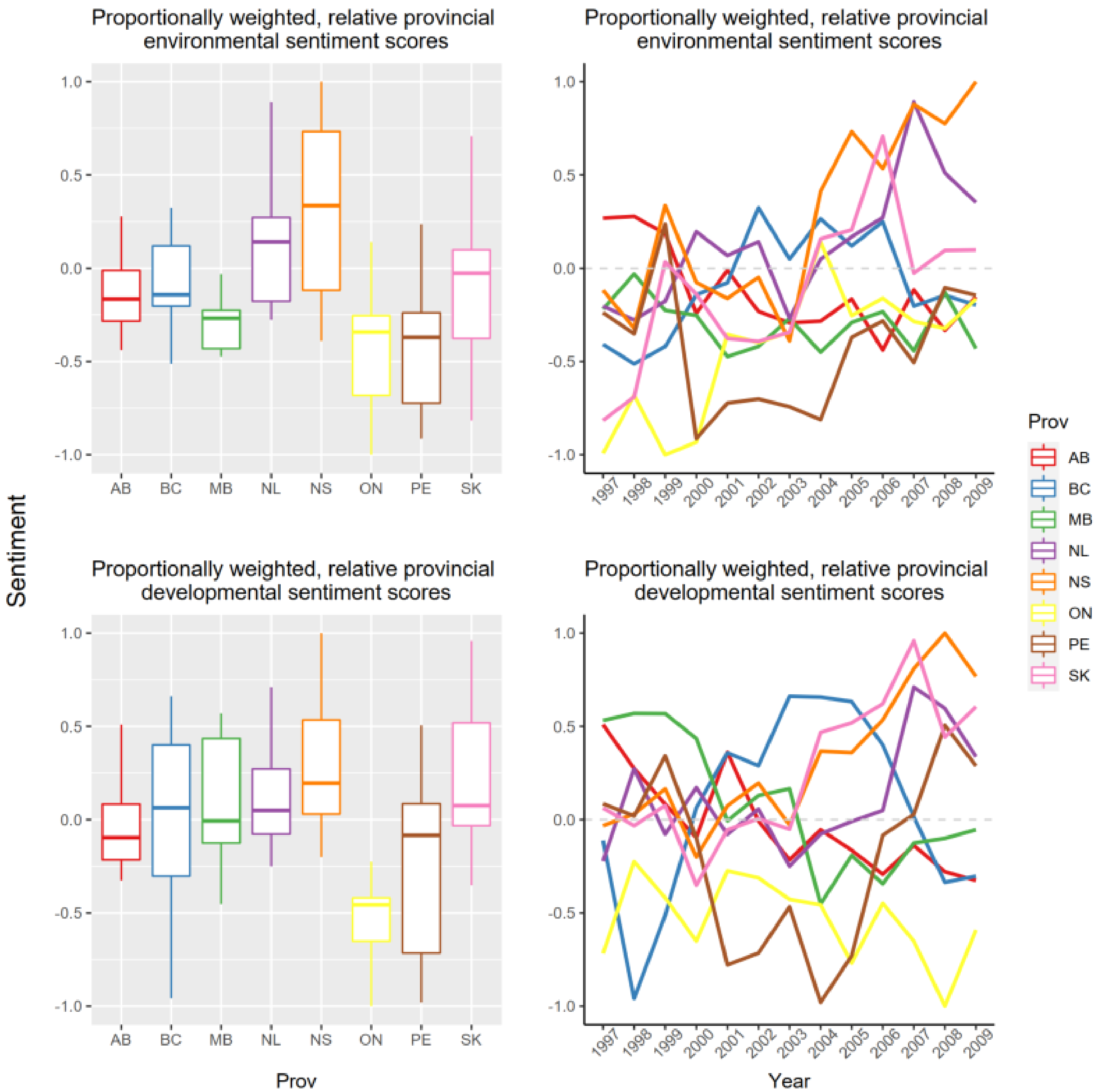


Figure 3.7| Proportionally weighted, relative environmental (top row) and developmental (bottom row) sentiment scores for provinces, calculated using provincial Hansards. The plots have been centred on 0 to visualize the relative placement of each province, so a negative value does not mean that that province has more negative sentiments than positive, but that the negative to positive sentiment ratio is higher relative to the other provinces present. The left column visualizes this data using boxplots while the right column visualizes this data from 1997 to 2009 using a line graph.

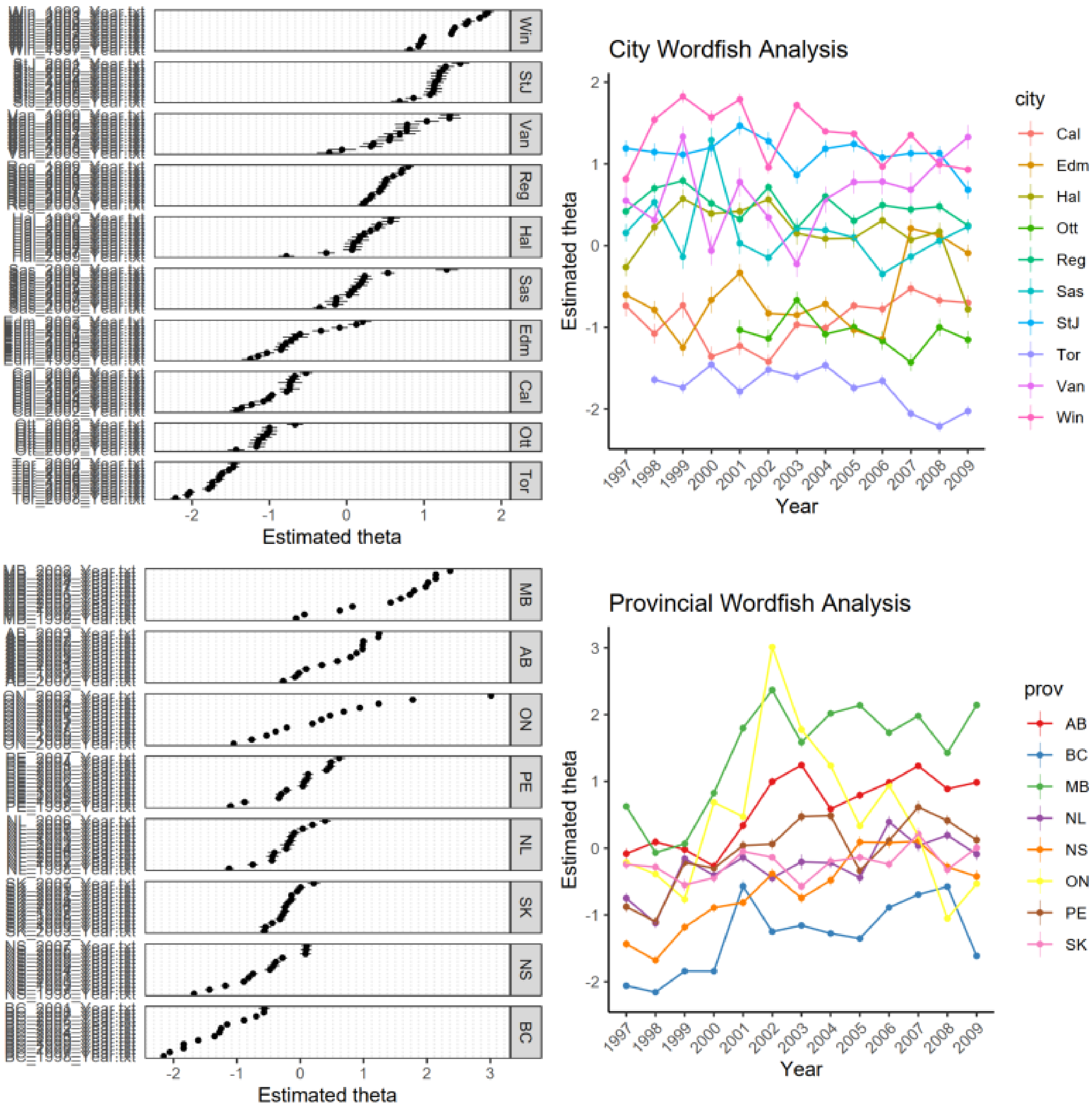


Figure 3.8| Wordfish theta values for cities (top row) and provinces (bottom row) calculated using city council minutes and provincial Hansards. These theta values provide an estimate of the relative policy space placement of each city/province along a developmental/environmental policy spectrum. More negative theta values are interpreted to be more strongly focused on development discussions, while more positive values are interpreted to be more strongly focused on environmental discussions within each city

council/provincial legislature. The closer two values are on the spectrum, the more similar the policy discussion between those two values. It should be noted that this positioning only relates to the topics of discussion, not the sentiment of those discussions (i.e., it does not relate to the positive/negative sentiment for each discussion piece). The left column dot plots display theta values from minimum to maximum, organized by city/province. The right column line graphs show how the wordfish scores change over time, organized by city/province. The 95% confidence intervals are shown as the horizontal lines in the left column and vertical lines in the right column for each wordfish score

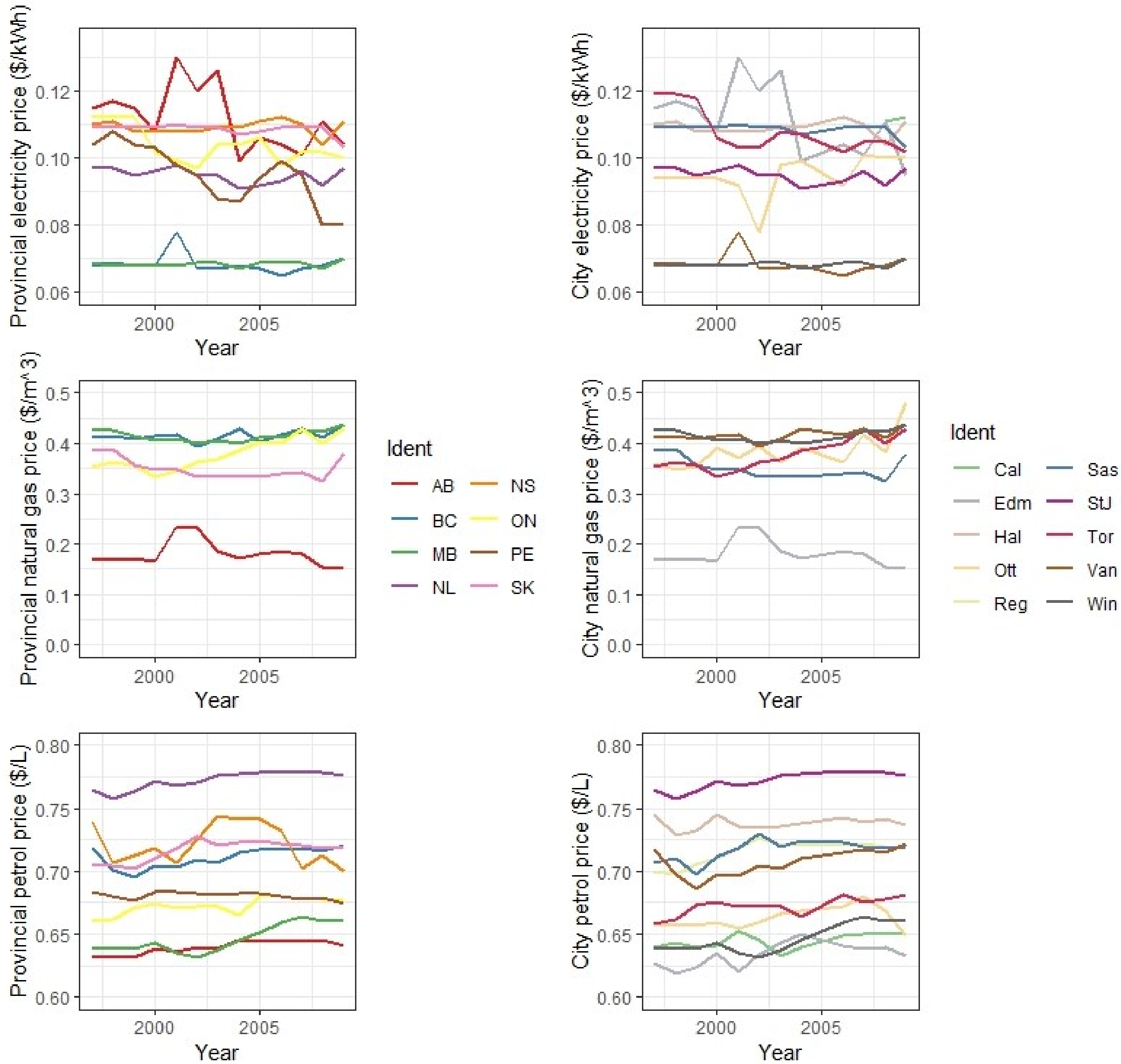


Figure 3.9| Annual energy source prices in 2002 Canadian dollars for provinces (left column) and cities (right column). The top row presents electricity prices ($/kWh). These values come from (Hydro-Québec, 2021) and are only reported for selected CMAs within each province. Where two or more cities were reported within one province, an average weighted by population of those cities was used to calculate the provincial prices. The middle row presents natural gas prices ($/m^3). Monthly natural gas prices were obtained from (Statistics Canada, 2021) and average per annum to get annual prices. These prices

were only available at the provincial level, so city prices come from the provincial price for which those cities are found. The bottom row presents petrol prices ($/L). These prices were calculated using CMA monthly averages obtained from (Statistics Canada, 2021) and averaged per annum to get annual prices. Provincial prices were calculated by using averages weighted by population for the available CMAs within that province.

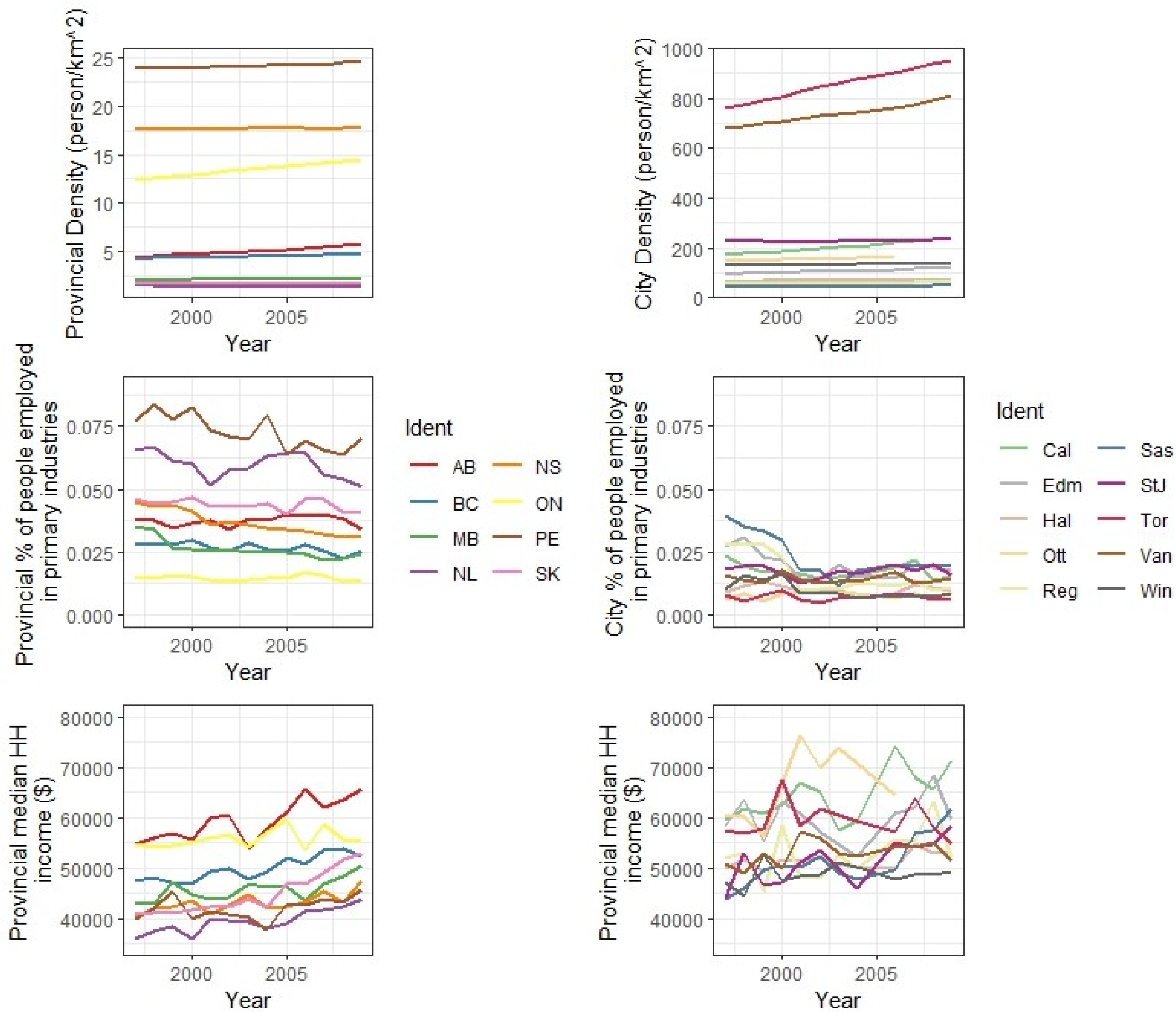


Figure 3.10| Population density (top row), percentage of people employed in primary industries (middle row), and median household income (bottom row) for provinces (left column) and cities (right column).

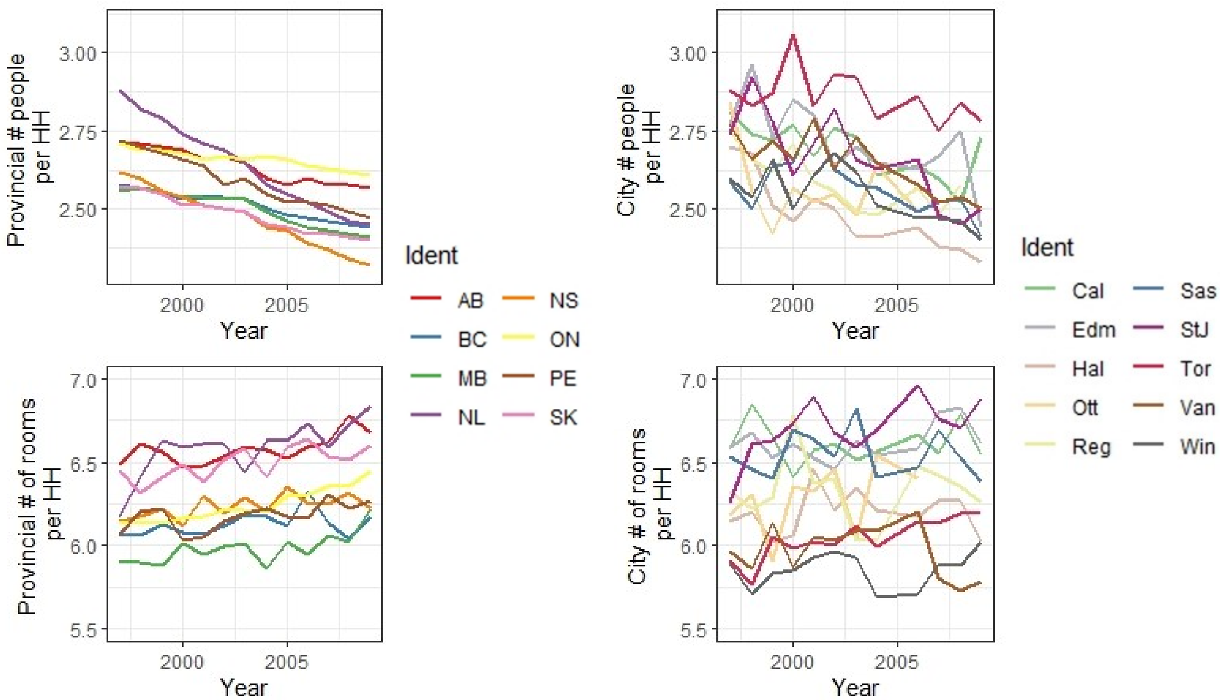


Figure 3.11| Average number of people per household (top row) and average number of rooms per household (bottom row) for provinces (left column) and cities (right column).

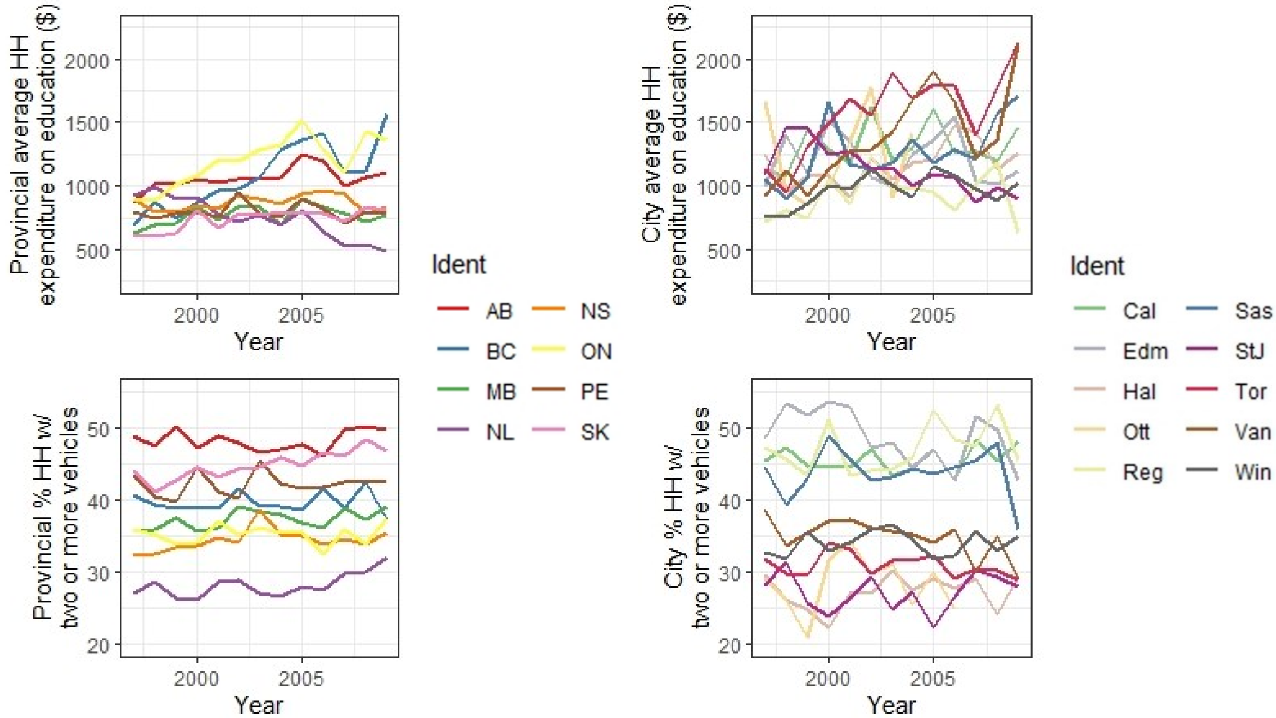


Figure 3.12| Average household expenditure on education in 2002 Canadian dollars (top row) and percentage of households with 2 or more vehicles (bottom row) for provinces (left column) and cities (right column).

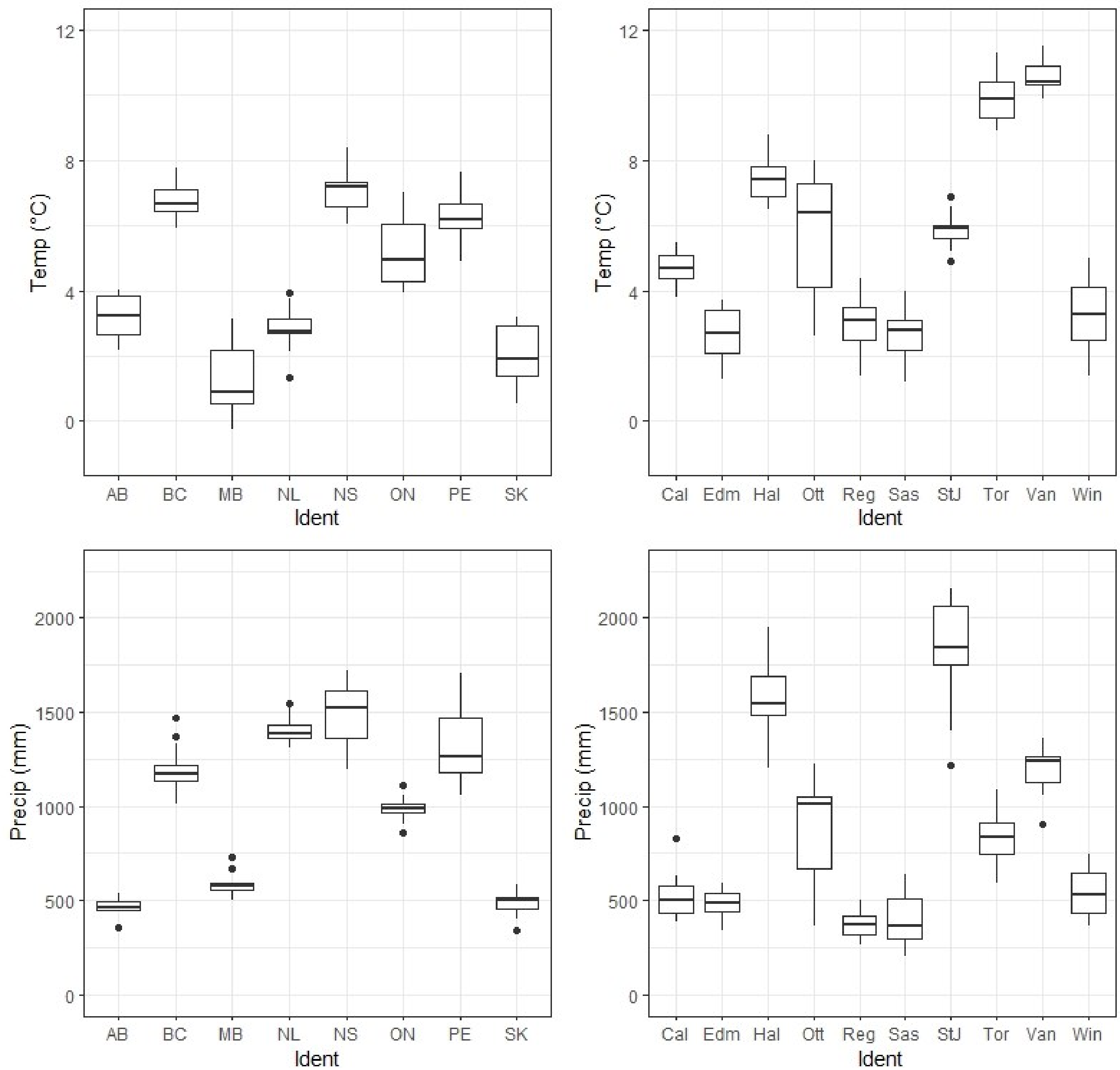


Figure 3.13| Average annual temperature (top row) and average annual precipitation (bottom row) for provinces (left column) and cities (right column). Provincial weather values were averaged across all weather stations within each province to get the provincial average.

Chapter Four: Quantifying the drivers of CO_2 emissions across Canadian Communities

4.1 Abstract

CO_2 emissions from community-based consumption are a major contributor to global greenhouse gas emissions. However, little is understood about how the variation in demographic, socioeconomic, and household factors across communities may contribute to CO_2 emissions. For example, the factors affecting CO_2 emissions of suburban neighborhood can be different than those affecting emissions of inner city or rural communities. Quantifying the nuanced effects of these factors on emissions is imperative for the successful development of community-based climate change mitigation and adaptation policies. Using quantile regression, we modeled these effects on different quantiles of community emissions for 1679 communities across Canada and each province in 2015. The results showed that population, followed by affluence, were the most important variables affecting total community emissions, while affluence was the most important factor affecting per capita community emissions. However, the effect sizes on emissions were not consistent across quantiles, decreasing for population and increasing for affluence from low to high community emission quantiles. In addition, our measure of poverty was associated with increases in total and per capita emissions for all quantiles. Our finding that the importance of the factors driving CO_2 emissions varied across communities of different quantiles suggests that successful emission reduction policies must take account of the contingencies of communities, particularly by considering the variation in population and affluence of communities. Our study also shows poverty alleviation is an effective means for CO_2 emission reduction and should be considered when adopting climate mitigation and adaptation policies.

4.2 Introduction

As the human population continues to grow and urbanization intensifies (Sun *et al.*, 2020), procuring the resources to support the global population has caused severe environmental damage to the global biosphere. Of that, the release of climate changing greenhouse gas (GHG) emissions is considered a major culprit (Hoegh-Guldberg *et al.*, 2019). The ability of national and subnational jurisdictions to employ policies that reduce GHG emissions is paramount to our success to navigate the current climate crisis (Rockström *et al.*, 2017). There is ongoing discussion as to what policy choices are best, with some arguing for tight "top-down" control by international, national, and subnational governmental bodies (Biermann *et al.*, 2012). Yet others argue that "bottom-up" community-based programs that are unique to each community are potentially more effective to address climate change related risks (van Aalst, Cannon and Burton, 2008). Still others argue that the policy toolbox should include both "top-down" and "bottom-up" policy choices to maximize the strengths (or minimise the weaknesses) of these choices (Cerna, 2013; Conway *et al.*, 2019).

A critical question underlying this debate is how do GHG emissions vary across communities. Our current knowledge about this variation is still limited, handicapping our ability to make sensible climate policy decisions. It is well established that nations vary hugely in GHG emission releases (Althor, Watson and Fuller, 2016; Yuan *et al.*, 2022), with many factors that drive these emissions being identified (Jorgenson *et al.*, 2019), and that recognition of these national differences in emissions is key to the success of international climate change negotiations (Wei *et al.*, 2012; Diffenbaugh and Burke, 2019; Rogelj *et al.*, 2019). However, much less is known about the variation within a society or a nation and how that variation would impact climate change mitigation and adaptation policies (Dodman and Mitlin, 2013; Hsu *et al.*, 2019; Ottelin *et* *al.*, 2019; Heinonen *et al.*, 2020; Kuramochi *et al.*, 2020). Nations are ultimately responsible for their total emissions, but it is the sum of the impacts of actions at local scales that contribute emissions to the national total, making it necessary to identify the differences in emission variation across local jurisdictions for making effective policy decisions (Corfee-Morlot *et al.*, 2009). As such, local governance must play a more central role in global emission reductions by bridging international and national emission reduction commitments with local initiatives that realize true emission reduction (Corfee-Morlot *et al.*, 2009; IPCC, 2014). Policies that are uniformly applied across communities lead to suboptimal outcomes because the uniqueness and differences across these communities, such as the built environment, differing consumption and lifestyle choices, or different degrees of urbanization (e.g., suburban, inner city, or rural), are not fully considered in these policies (Ottelin *et al.*, 2019). Recognition of these differences is a necessary step in maximizing local capacity to reduce GHG emissions, allowing for the local socioeconomic needs of these communities to be integrated into broader subnational, national, and international climate change strategies and policies (IPCC, 2018; Hsu *et al.*, 2019). Furthermore, the drivers of local, community-level emissions are nuanced and can change widely, depending on the demographic, societal, economic, climatic, and political characteristics of each community (Newell, 2008; Jones and Kammen, 2011; IPCC, 2014; Allan and Hadden, 2017; Jorgenson *et al.*, 2019).

Quantifying the variation of GHG emissions and their drivers is necessary to facilitate the development of policies that recognize the differences of local communities and their varied capacity in reducing GHG emissions. These differences across communities may include the population or population density of a community (Oliveira, Andrade and Makse, 2014; Güneralp *et al.*, 2017; Ottelin *et al.*, 2019; Goldstein, Gounaridis and Newell, 2020); household-level characteristics like the use of high quality insulation and energy efficient appliances, household income, and the number of household members (Adua *et al.*, 2019); societal-level characteristics like the prevalence of income inequality (Cheng *et al.*, 2021); or through a combination of these and additional factors (Rosa and Dietz, 2012; Jorgenson *et al.*, 2019). Moreover, how the influence of these factors translate into increases or decreases in emissions remains ambiguous. For example, there is ongoing debate about the effect of population on emissions. It has been argued that per capita emissions decrease as communities increase in size due to economies of scale (Wang, Madden and Liu, 2017). However, other studies have shown that per capita emissions remain approximately the same regardless of population size (Fragkias *et al.*, 2013) or even increase as communities increase in population and productivity (Oliveira, Andrade and Makse, 2014). Arguments for lowering emissions through ecological modernization (Bailey, Gouldson and Newell, 2011) are challenged by others who state that affluence inherently drives emission increases because affluence is linked to higher consumption regardless of the level of industrialization or technological prowess of a nation or society (Wiedmann *et al.*, 2020), while other research has shown that both of these arguments are inconclusive and require further investigation (Jorgenson and Clark, 2012). Income inequality and poverty may limit emissions due to the inability of those from a lower socioeconomic status to consume at similar rates of those who are more affluent (Hwang and Lee, 2017), but may also increase emissions by over-consumption choices of the super-rich (Otto *et al.*, 2019), or even increase emissions in the short term but decrease emissions in the long term (Liu, Jiang and Xie, 2019). Characteristics of urban form, such as population density, and access to low emission amenities, such as public transit, can affect both increases and decreases in community emissions when other factors are controlled for (Makido, Dhakal and Yamagata, 2012). These incongruences across studies suggest that we still do not fully understand the complex nuances that drive community-level emissions.

The variations and incongruences across community-level emissions entail a better understanding of the nuances that drive community emissions. In this study, we use quantile regression (QR) to quantify the effects of demographic, socioeconomic, and household variables on community-level CO_2 emissions, a major constituent of GHG emissions. We are particularly interested in identifying which variables are consistently responsible for the CO_2 emissions across all communities and which variables have varied effects on the emissions of different communities (e.g., low-emitting vs high-emitting communities). We compiled a database on CO_2 emissions from 1679 communities across Canada. Different from traditional regressions, QR models the structure of the data across quantiles in a way that reveals the nuanced effects of explanatory variables on CO_2 emissions at different quantiles that would otherwise not be revealed. This quantile-based analysis is necessary for determining potential policy solutions that recognize and appreciate the uniqueness of each community because communities with different GHG emission levels can be subjected to the effects of a very different set of factors. Any adaptation and mitigation policy that does not take account of these variations will provide suboptimal outcomes. Our results show that population was the most important driver of total community emissions, having a stronger effect size on the lower quantiles of community emissions, followed by affluence. Affluence was the most important driver associated with per capita community emissions, where it increased emissions but differed from the effect of population size as it had the greatest effect sizes on the upper quantiles of emissions. This study reveals that factors responsible for CO_2 emissions vary across low and high emitting communities and highlights the importance of considering community disparities while making climate mitigation policies. Policies that blindly apply across all communities will be suboptimal at best or fail.

4.3 Methods

4.3.1 Data

We compiled data on per-capita and total CO_2 emissions for 1679 Canadian communities. We obtained a gridded estimate of carbon footprints across Canada from the Global Gridded Model of Carbon Footprints (GGMCF; Figure 4.1; Moran et al., 2018), as raw emission data were not available across these communities. The GGMCF provides an estimate of per-capita consumption-based CO_2 footprints across the globe for the year 2015, with a spatial resolution of 250 metres. This database has been used in other studies which include estimating the urban contributions to global GHG emissions (Gurney *et al.*, 2022), the analysis of the carbon footprint of megacities (Paravantis *et al.*, 2021), and the effect of “smart” city design on urban per capita emissions (Garcia, Vale, and Vale, 2021).

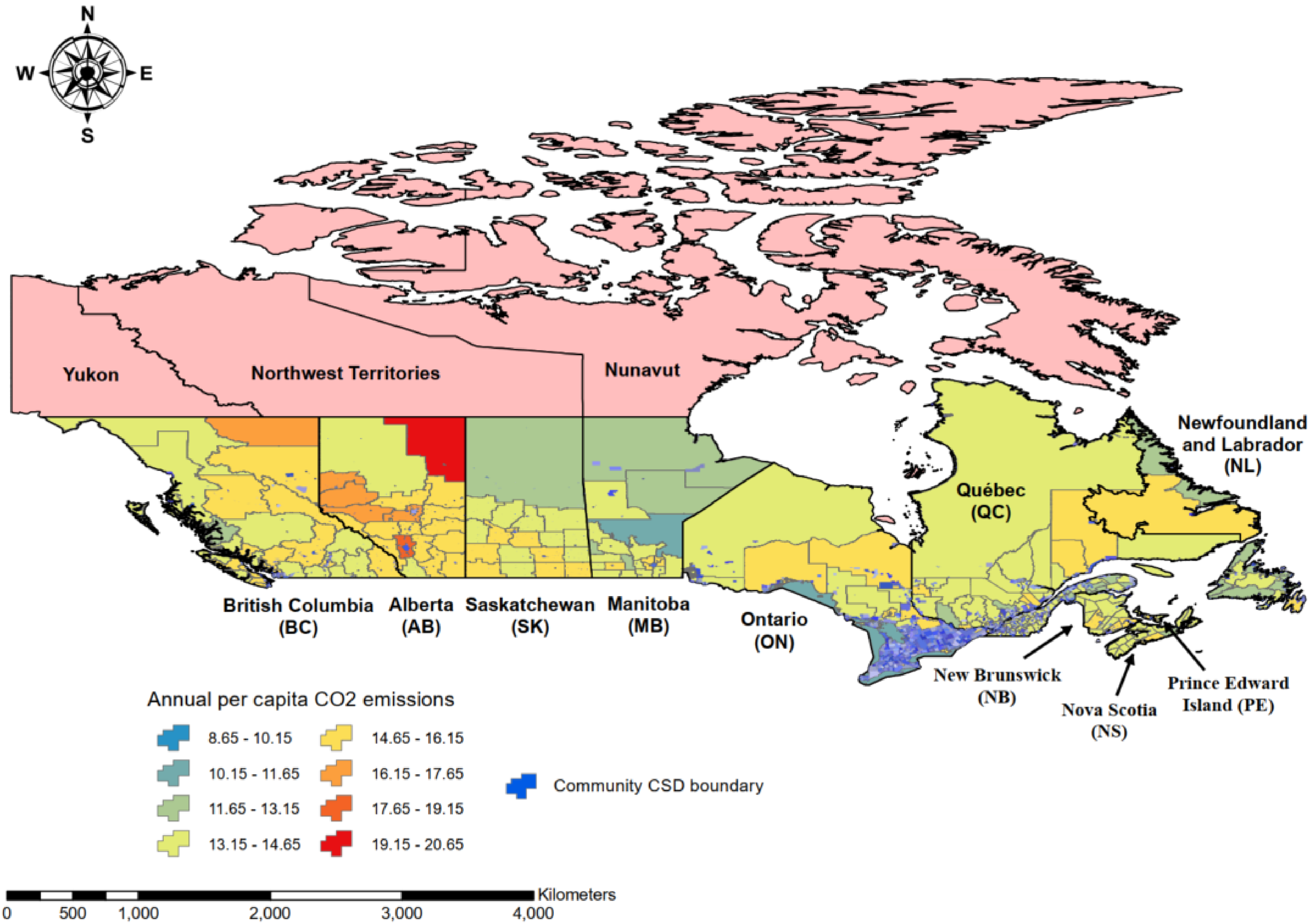

N
S
E
W
Yukon
Northwest Territories
Nunavut
Newfoundland and Labrador (NL)
Québec (QC)
British Columbia (BC)
Alberta (AB)
Saskatchewan (SK)
Manitoba (MB)
Ontario (ON)
New Brunswick (NB)
Nova Scotia (NS)
Prince Edward Island (PE)
Annual per capita CO2 emissions
8.65 - 10.15
10.15 - 11.65
11.65 - 13.15
13.15 - 14.65
14.65 - 16.15
16.15 - 17.65
17.65 - 19.15
19.15 - 20.65
Community CSD boundary
0
500
1,000
2,000
3,000
4,000
Kilometers

Figure 4.1| Map showing the 1679 communities in this study and estimates of annual per-capita consumption-based GHG emissions (t CO2) across Canada in 2015. Community boundaries are defined by census subdivisions obtained from the 2016 Canada census (Statistics Canada, 2019). The different blue hues are to help visualize the delineation between CSD boundaries. The territories were not included due to lack of LICO data (light red). Emission estimates were obtained from the Global Gridded Model of Carbon Footprints at a spatial resolution of 250 metres (Moran et al., 2018; accessed from http://citycarbonfootprints.info/)

To estimate community-level emissions, we used census subdivision (CSD) boundaries defined by the 2016 Canadian census (Statistics Canada, 2019). Due to the Canadian census being conducted every five years, we chose the 2016 census as it was closest to the 2015 carbon footprint data of the GGMCF. CSDs labelled as counties, parishes, regional districts, reserve lands, or the alike were excluded. In cases where a community was located across the border of two provinces (e.g., Lloydminster on the Alberta and Saskatchewan border), the majority rule was used to assign the community to the province which had most of the population for that given community. This yielded 1679 communities with a population ranging from 252 people in Fox Harbour, Newfoundland and Labrador to 43,363,148 people in Toronto, Ontario, and land area ranging from 0.59 km^2 in Hay Lakes, Alberta to 3084.38 km^2 in Kawartha Lakes, Ontario (Figure 4.1).

Using ArcGIS Desktop (ESRI, 2019), the gridded emissions from the GGMCF and CSD boundaries were overlayed, and total community CO_2 emissions were calculated by multiplying the gridded per-capita CO_2 emissions by the population of each community. Since the GGMCF is gridded with a 250m resolution, many community boundaries contained multiple GGMCF grid squares with differing per-capita emission values. A weighted average of per-capita emissions was calculated for these communities using the percent area of cover by grids of differing emission values. Some communities located on a water body did not have complete coverage from the GGMCF. Emissions for these communities were calculated using the coverage available. Table 4.1 provides summary statistics for per capita and total emissions for communities across Canada and each province.

In addition to the CO_2 emission data, we also compiled variables that represent demographic, socioeconomic and household level activity data for each community from the 2016 Canada census (Statistics Canada, 2017). These variables consist of population; population density per km^2; percentage of people that commute 60 minutes or longer a day to work; percentage of employment in natural resources, agriculture and related production occupations; average age of the population; average household size; average number of rooms per household dwelling; median total income in 2015 among recipients; percentage of population with no certificate, diploma or degree; percentage of population with low income based on the low-income cut-offs (LICO), after tax; and unemployment rate (Table 4.2; Figures 4.4 – 4.14, Section 4.7). The number of people commuting over 60 minutes a day, employment in production occupations, and population with no certificate variables were originally reported as count data per community. These values were converted to percentage of population by dividing the count data by the population of each community. Due to unavailable LICO data for the Canadian territories, the territories were not included in this study.

Table 4.1| Summary statistics for tonnes of community CO_2 emissions across all Canadian communities in this study, organized by each province. The blue (top) portion of the table shows the statistics for total community emissions. The orange (bottom) portion of the table shows the statistics for per capita community emissions. Provincial abbreviations are defined in Figure 4.1.

Province	Min	Max	Mean	Median	StDev	*n*
Canada (total)	**3,247**	**43,363,148**	**275,980**	**29,082**	**1,616,361**	**1,679**
AB	3,921	21,817,245	302,675	23,701	1,963,058	184
BC	3,921	9,477,198	411,036	75,729	1,141,614	144
MB	3,744	10,561,319	359,676	42,963	1,728,072	37
NB	4,066	1,051,478	75,632	18,212	182,284	88
NL	3,426	1,624,201	39,398	9,791	139,674	157
NS	6,591	171,432	56,620	44,791	45,682	22
ON	4,360	43,363,148	520,065	96,858	2,530,341	396
PE	3,462	522,544	42,252	5,567	106,820	27
QC	3,526	24,908,762	254,280	35,423	1,391,285	399
SK	3,247	3,860,537	55,779	9,359	344,785	225
Canada (per capita)	**11.7**	**18.5**	**14.6**	**14.5**	**1.0**	**1,679**
AB	14.1	17.8	15.8	15.7	0.9	184
BC	14.1	15.8	14.8	14.7	0.5	144
MB	12.5	15.6	13.8	13.8	0.7	37
NB	13.3	18.5	14.3	13.7	1.1	88
NL	11.7	15.7	13.9	14.1	1.0	157
NS	13.1	14.4	13.8	14.0	0.4	22
ON	13.2	17.9	14.9	14.8	0.6	396
PE	13.4	14.7	14.1	14.1	0.5	27
QC	12.8	18.5	14.1	13.9	0.8	399
SK	12.4	15.9	14.6	14.4	1.0	225

Table 4.2| Summary statistics for the independent variables across all Canadian communities in this study.

Variable	Unit	Min	Max	Mean	Median	StDev
Population	population logged	5.5	14.8	7.9	7.6	1.7
Population density	population/ km^2	0.2	5492.6	298.2	122.5	529.3
Commute 60+ minutes a day	% of population	0.0	19.8	3.4	2.7	2.6
Employed in primary industries	% of population	0.0	19.5	2.6	2.0	2.3
Average age	age of population	24.4	60.1	43.6	43.8	5.1
Household size	people per household	1.6	4.8	2.4	2.3	0.3
Number of rooms	rooms per household	3.8	9.4	6.7	6.6	0.6
Median income	Canadian dollars	9,712	89,293	33,811	33,024	7,061
Population with no certificate, diploma, or degree	% of population	0.0	57.9	19.6	18.5	7.5
Population below low income cut-off (LICO)	% of population	0.0	40.5	4.9	4.3	2.8
Unemployment rate	% of population	0.0	56.0	9.9	8.0	7.0

4.3.2 Statistical analysis

Our focus of analysis was to model total and per-capita CO_2 emissions across the study communities. We first tested for collinearity amongst the independent variables for the provincial data and Canada (provinces combined) data using a cut-off of Pearson's $R^2 \leq 0.90$ and detected no collinearity. The independent variables were then normalized to a range of 0 - 1 using $(x - x_{min})/(x_{max} - x_{min})$. The community emissions were modelled using quantile regression (QR) with the following form:

$$y_i = x_i'\beta_q + e_i$$

where y is the logged total CO_2 emissions or the per capita CO_2 emissions of the i^{th} community, x is a vector including the intercept and explanatory variables (the demographic, socioeconomic, and household variables introduced in Table 4.2), β_q is the coefficient of quantile q, $q \in [0, 1]$, and e_i is the model residuals. The QR model for total emissions did not include population density as an independent variable, while the QR model for per capita emissions did not include population as an independent variable. β_q can be estimated by minimizing the following function:

$$Q(\beta_q) = \sum_{i \in \{y_i \geq x_i' \beta_q\}} q \left| y_i - x_i' \beta_q \right| + \sum_{i \in \{y_i < x_i' \beta_q\}} (1 - q) \left| y_i - x_i' \beta_q \right|$$

The QRs were ran using each dataset with tau interval values (i.e., quantile q in the equations above) increasing by 0.2, starting at 0.2 and ending at 0.8. Because of an insufficient number of communities in Nova Scotia, the QR modeling for this province had a tau interval of 0.3 with a starting value of 0.35 and an ending value of 0.65. All analyses were conducted using R (R Core Team, 2022) and the package quantreg (Koenker, 2021).

4.4 Results

Annual tonnes of total consumption-based emissions varied across communities in Canada from 3,247 tonnes of CO_2 emissions for the community of Stony Rapids, Saskatchewan to 43,363,148 tonnes of CO_2 emissions for Toronto, Ontario (mean = 275,980; median = 29,082; standard deviation = 1,616,361), while per capita tonnes of emissions ranged from 11.7 in the town of Leading Tickles, Newfoundland and Labrador to 18.5 in the village of Baker Brook, New Brunswick (mean = 14.6; median = 14.5; standard deviation = 1.0; Table 4.1). Our QRs revealed that, overall, population was the strongest predictor of total community emissions, being consistently correlated with increasing emissions across Canada and within all provinces, with the effect size of population becoming smaller as community emissions increased across Canada (Figure 4.2). However, this pattern was not universal across communities of differing provinces (see Appendix A Figures A.1 – A.20 for the QR results of each province). For example, in Ontario, the population effect size becomes greater as total community emission quantiles increase (Figure A.13). Population density was not a significant predictor of per capita community emissions in most circumstances except for Alberta and Saskatchewan where it was associated with increasing per capita emissions at the lower tau value of 0.2, and Ontario where it was associated with increasing emissions for the tau values of 0.6 and lower (Figures 4.3, A.2, A.14, and A.20). Median income was associated with both total and per capita emission increases or was non-significant for most of our analyses. Additionally, where significant, the effect of income on emissions increased as tau values increased in most circumstances. LICO, our measure of poverty, was associated with increasing per capita and total emissions for all tau values at the national level. However, this measure was inconsistently correlated with community emissions or not significant for some provinces. For example, LICO was associated with decreasing total emissions for the tau value of 0.2 in Alberta (Figure A.1) but was associated with increasing emissions for the tau values of 0.6 and lower in Québec, becoming non-significant for the value of 0.8 (Figure A.17). The variables 'percentage of population with no certificate, diploma or degree' and 'unemployment' were both associated with lower total community CO_2 emissions and per capita emissions for lower tau values up to 0.4 across Canada, becoming non-significant above this value. These variables were largely non-significant across provinces with some exceptions. For example, unemployment in Alberta was associated with increasing total emissions and per capita emissions for all values of tau except 0.8 (Figures A.1 and A.2). Lastly, the percentage of residents that commute 60 minutes or longer a day to work was consistently associated with increasing per capita and total emissions for all values of tau across Canada. It was also associated with increasing emissions for all or most values of tau for the provinces of British Columbia, Newfoundland and Labrador, Ontario, Québec, and Saskatchewan.

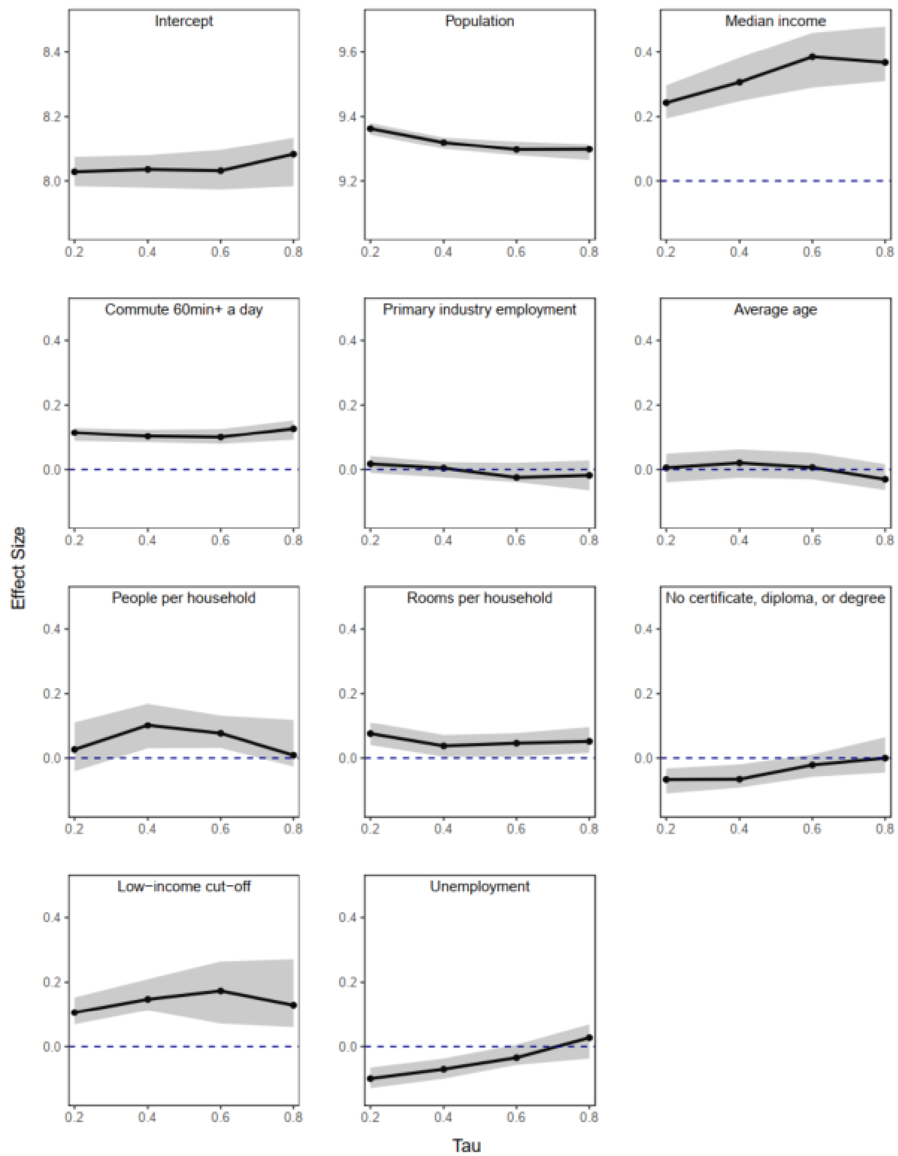


Figure 4.2| Quantile regression results for total community emissions (CO_2) across Canada, excluding territories due to lack of LICO data available for these territories. The *y*-axis represents the effect size of each variable, and the *x*-axis represents the quantiles (tau values) used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% confidence interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

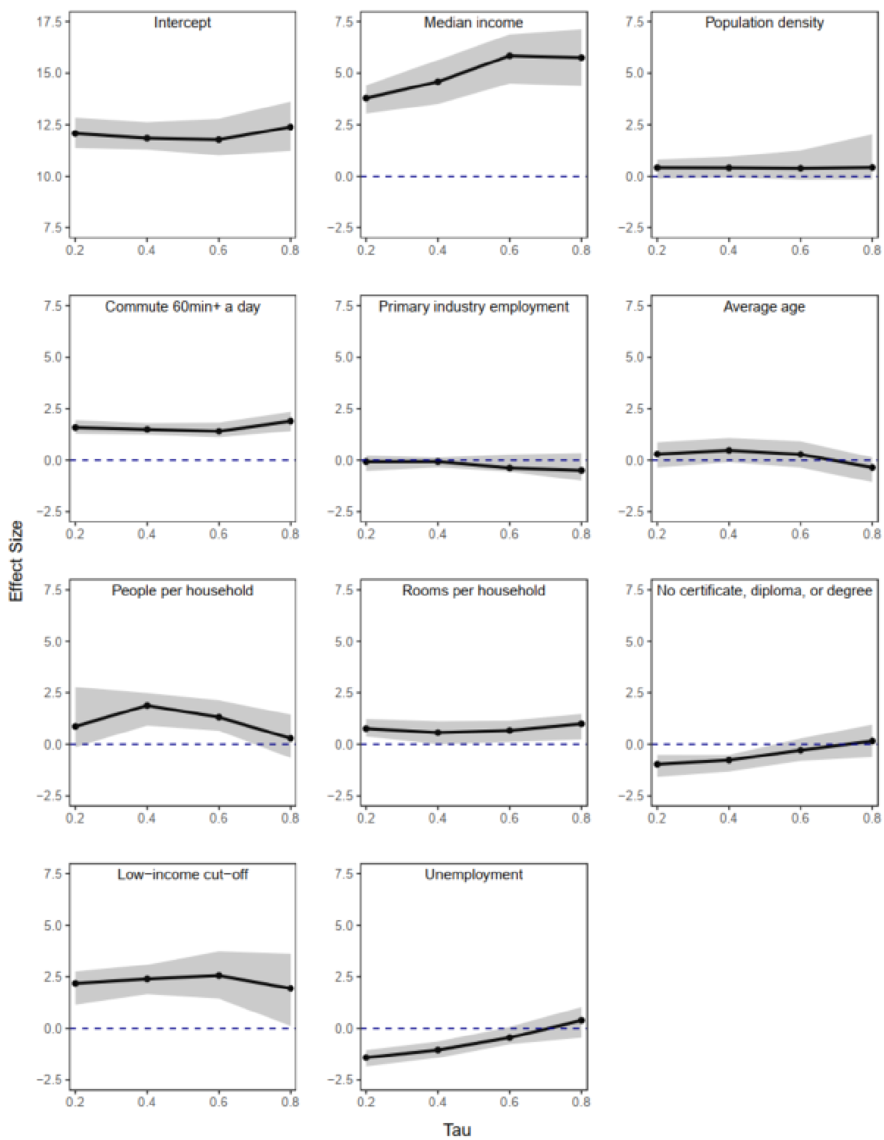


Figure 4.3| Quantile regression results for per capita community emissions (CO_2) across Canada, excluding territories due to lack of LICO data available for these territories. The *y*-axis represents the effect size of each variable, and the *x*-axis represents the quantiles (tau values) used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% confidence interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

4.5 Discussion

As global urbanization continues, the ability of communities to develop strategies and policies to limit local GHG emissions is paramount to mitigate and adapt to climate change (Corfee-Morlot *et al.*, 2009). International panacea strategies and policies that attempt to address the causes and risks of climate change often do not have the desired impact or outcome because it is at the local and regional scales that the impacts of climate change are experienced and emissions are released (Corfee-Morlot *et al.*, 2009; Seneviratne *et al.*, 2016). As such, developing effective emission mitigation policies entails that we understand how emissions vary from one community to the next (Moran *et al.*, 2018). Due to the nuances found in each community, the effects of the drivers of GHG emissions may change in subtle yet important ways relative to which quantile of emission releases is being analyzed (Cheng *et al.*, 2021). Because of these nuances, it is still unclear as to what the optimum community-level policies may be if the goal of optimization is to limit GHG emissions.

In this study we use QR to illuminate some of these nuances, allowing for insights into how the drivers of community CO_2 emissions change from smaller to larger emitting communities. We found that both population and affluence were major drivers of CO_2 emissions across Canada and within many provinces (Figures 4.2–4.3; Appendix A Figures A.1–A.20). However, the impact of these drivers on emissions changed relative to the quantile being examined. Furthermore, effective policies may have societal co-benefits. For example, our results provide evidence that successful poverty reduction initiatives may also have the co-benefit of lowering both per capita and total community emissions. Additionally, utilizing QR to explore the nuances of the drivers of emissions across communities has the potential to enhance targeted emission reduction policy decision making.

4.5.1 Population and population density

Overall, population was shown to be the most important factor associated with total community emissions, increasing emissions across Canada and within each province. These results are not surprising as population has been found to be a major driver of GHG emissions (Rosa and Dietz, 2012; Oliveira, Andrade and Makse, 2014; Ribeiro, Rybski and Kropp, 2019). However, our analysis revealed important variation across communities with different levels of emissions and provided evidence that the influence of population on emissions decreased as quantiles of community emissions increased at the national level and in many provinces. This finding does not support some studies that show that the impact of population on emissions scales linearly with community size (Fragkias *et al.*, 2013), or population becomes more impactful on emissions as community size increases (Oliveira, Andrade and Makse, 2014; Ribeiro, Rybski and Kropp, 2019). Instead, our findings suggest that, within the Canadian context, there may be an economy of scale between population and total community CO_2 emissions where the effect size of a changing population on emissions is greater in smaller communities than larger communities.

There is much debate on whether increasing population density would increase or decrease overall emissions. Some evidence suggests that population density can lower emissions through emergent economies of scale, such as sharing warmth in multiple dwelling buildings or less vehicle usage due to the closer vicinity of amenities (Glaeser and Kahn, 2010; Wang, Madden and Liu, 2017). Other evidence suggests that a high population density may increase emissions due to the heating of additional buildings required to support the high density of people regardless of whether people occupy these buildings or not (Zarco-Periñán, Zarco-Soto and Zarco-Soto, 2021). Still, additional evidence shows that per capita emissions from population density follow an inverted U-shaped relationship where a low density increases emissions, plateaus for mid-density, and then decreases at a high density (Lin *et al.*, 2022).

Our results show that population density was not associated with per capita emission variation across Canada and within provinces, with the exceptions of Alberta, Ontario, and Saskatchewan. This suggests that, given Canada has one of the lowest population densities in the world (World Bank, 2021), density is not yet a major contributor to emission increases or decreases in Canada. To explain this, many Canadian communities may not have reached a critical population density that would create an effect on emission increases or decreases. However, as community densities increase across Canada, strategizing key features of urban form and energy efficient technologies which promote low-carbon communities could play a significant role in limiting future community emissions (Güneralp *et al.*, 2017).

4.5.2 Affluence and poverty

The steady increase in affluence across the globe since the middle of the 20th century has proven to be one of the leading factors propelling humanity into our current global environmental emergency (Wiedmann *et al.*, 2020). Across Canada and most provinces, income (our measure of affluence) was shown to be a major contributor to increases in both per capita and total community CO_2 emissions (Figures 4.2, 4.3, A.1–A.20). Additionally, income had a greater impact on increasing emissions as tau values increased in most circumstances. This suggests that in larger urban centres the consumptive behaviours of those with more affluence has a greater CO_2 emission footprint than those with the same level of affluence living within smaller communities. An explanation for this finding is that conspicuous consumption is more prevalent in larger communities than smaller communities. It has been reported that increases in city population and population density were both correlated with increases in conspicuous consumption (Currid-Halkett, Lee and Painter, 2019), strengthening the argument that affluence intensifies environmental stress (Wiedmann *et al.*, 2020), while increasing emission releases in the process.

Related to affluence is the LICO variable, our measure of poverty. It is possible for poverty to influence emission trends in many ways. Poverty may increase emissions through the inability of those from a lower socioeconomic status (SES) to access energy efficient technologies, such as quality household insulation, or access information about energy efficient household practices (Reames, 2016). Poverty may also increase conspicuous consumption amongst those from a lower SES as they imitate the consumption habits of society's wealthy (Cushing *et al.*, 2015). Moreover, there are additional institutional, social, and regulatory barriers to the adoption of energy efficient household practices by those in a lower SES, such as distrust in the public institutions that promote energy efficient solutions (Reames, 2016). However, poverty may also decrease emissions. For example, an unequal distribution of wealth may inhibit non-essential consumption of those from a lower SES to such a degree that total emissions decrease, even when the extravagant consumptive lifestyles of those from a higher SES are considered (Berthe and Elie, 2015; Hwang and Lee, 2017). Thus, a more equal distribution of wealth could increase the overall societal consumption of non-essential goods and services, leading to the release of more emissions from this consumption. Additionally, the effects of poverty on emissions may change over time. For example, income inequality in the United States may increase emissions in the short term yet decrease emissions in the long term (Liu, Jiang and Xie, 2019).

Our findings support the position that poverty is associated with a net increase in both per capita and total community CO_2 emissions for all quantiles at the national level (Figures 4.2 and 4.3). This indicates that developing policies that address economic disparity could be a valuable means for communities to lower their CO_2 emission footprint. As such, policies that look at effective redistribution of resources and wealth across a nation's population may be promising in reducing poverty while also contributing to a low carbon future (Jorgenson, Schor and Huang, 2017; Soergel *et al.*, 2021).

4.5.3 Unemployment and education

Both the percentage of population with no certificate, diploma or post-secondary degree and unemployment were associated with decreases in per capita and total community CO_2 releases for tau values at and below 0.4 across Canada, and these effects were more pronounced as tau values decreased (i.e., for the communities of low quantile emissions). These findings are counter-intuitive because higher unemployment and lower levels of education have both been linked to an increase in poverty (Brady, Finnigan and Hübgen, 2017), suggesting that these measures would also potentially increase overall emissions like our LICO variable discussed above. However, given that unemployment inhibits the ability of a person to engage at the same level of consumption as those who are employed (Ganong and Noel, 2019), this consumptive inhibition could explain why unemployment is correlated with less emissions, at least for lower tau values. Furthermore, a correlation between less formal education and lower emissions may be linked to conspicuous consumption. Research has shown that people who obtain a higher level of education are more likely to engage in behaviours of conspicuous consumption (Memushi, 2013). This finding coupled with evidence that conspicuous consumption may be more rampant in urban vs rural settings due to an increase in social interactions and access to mass media (Hwang and Lee, 2017), may explain why our results show that the lack of education is associated with lower consumption-based CO_2 emissions, and that the magnitude of this association becomes stronger as tau values decrease.

4.5.4 Policy implications

Utilizing QR to analyze community emissions data reveals nuanced insights about the drivers of GHGs that traditional regression methods do not offer. Specifically, QR distinguishes between drivers that consistently affect GHGs across all communities and drivers that have varied effects on the GHGs of different communities (e.g., low-emitting vs high-emitting communities). Distinguishing between such drivers allows policymakers to identify emission reduction solutions that acknowledge the uniqueness of each community, avoiding the development of panacea emission reduction policies in situations where such policies would deliver suboptimal emission reduction outcomes. Furthermore, QR provides clarity into the potential effects that "top-down" and "bottom-up" policies could have on overall community GHGs. For example, our findings suggest that supporting poverty and economic disparity reduction initiatives could be an effective means of limiting GHG emissions. Investment in such initiatives could be integrated across multiple levels of government, civil society, and NGOs (Newell, 2008; Allan and Hadden, 2017), being justified as joint initiatives that benefit those from a lower SES while also benefitting society through lower GHG emissions (Jorgenson, Schor and Huang, 2017), lower crime rates (Gaitán-Rossi and Velázquez Guadarrama, 2021), lower suicide rates (Kerr *et al.*, 2017), increased climate risk adaptation (Hallegatte and Rozenberg, 2017), and similar beneficial outcomes. The costs to implement such policies could be compensated by the many co-benefits these policies generate (Thompson *et al.*, 2014). However, society must decide that the effort required for successful emission mitigation and adaptation takes precedent over other economic concerns (Hoegh-Guldberg *et al.*, 2019), and it must happen immediately (Forster *et al.*, 2020), if we are to provide a just, democratic, and sustainable world for future generations.

4.6 Supplementary information for Chapter Four

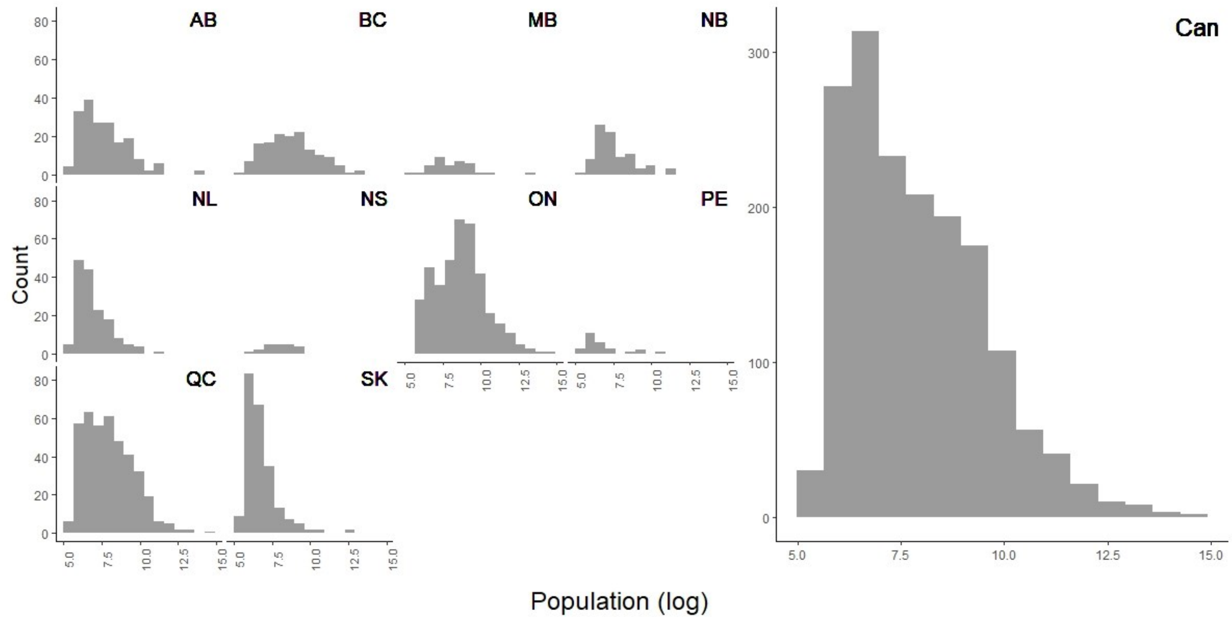


Figure 4.4| Histograms showing the population distribution for Canada and each province. Population values are logged.

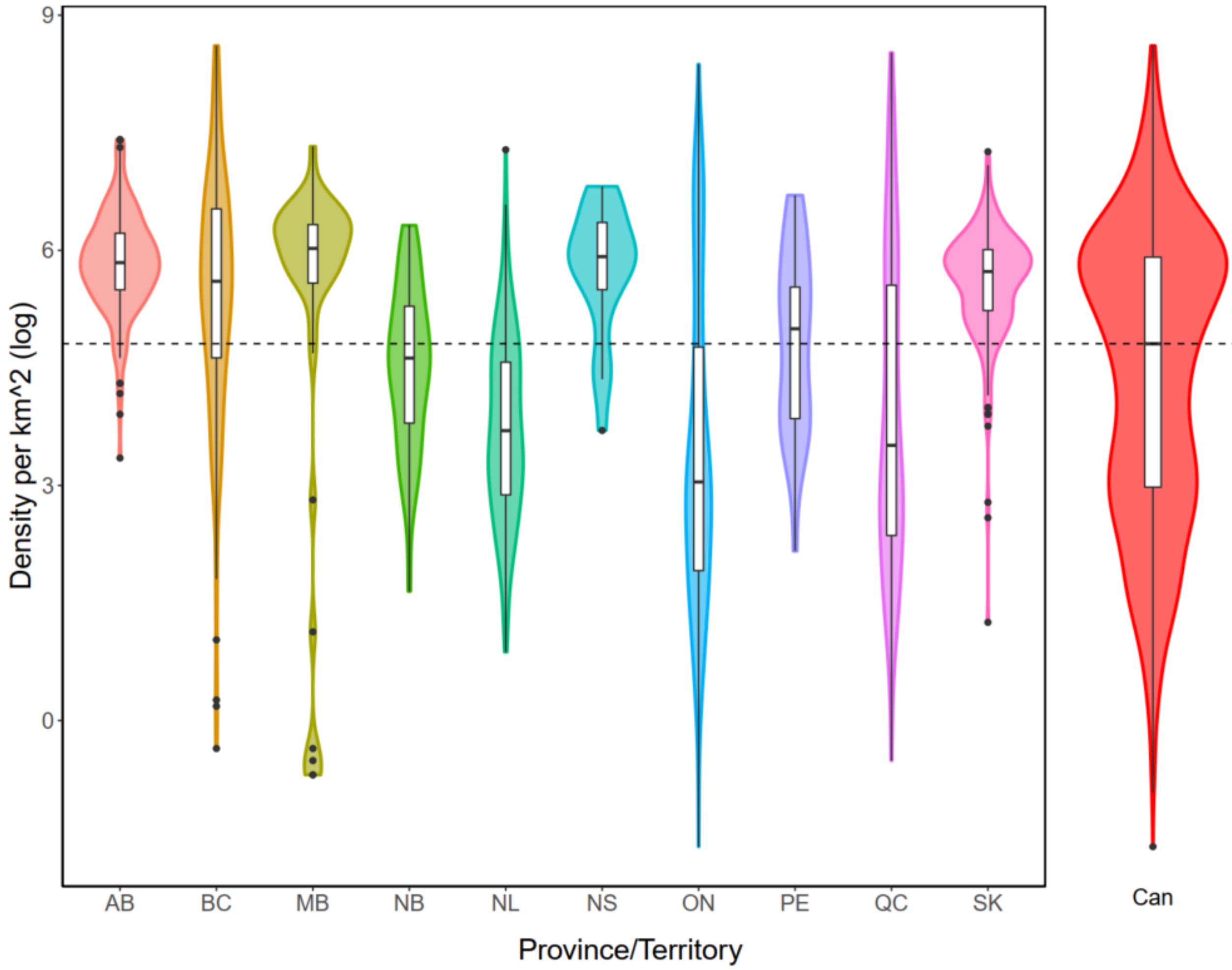


Figure 4.5| Violin graphs showing the distribution of population density (population/km^2), for Canada and each province. Box plots are overlayed over the violin graphs to show median, quantiles, and outliers in the data. Density values are logged. The dashed line represents the median value for Canada.

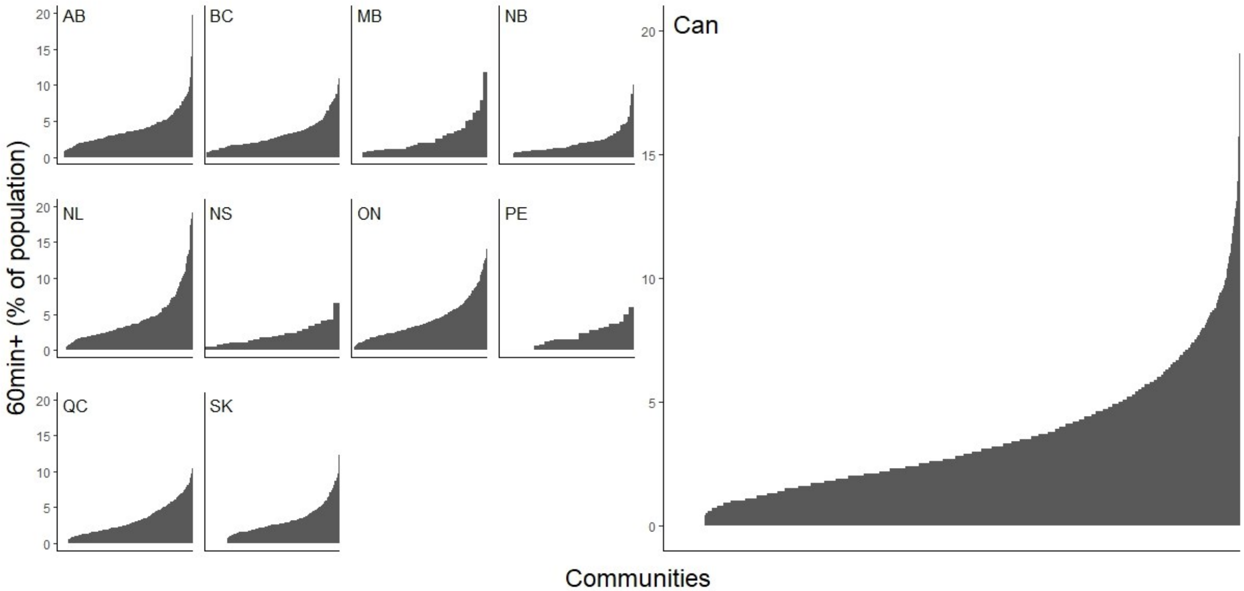


Figure 4.6| Histograms showing the percentage of population commuting 60 minutes or longer a day for Canada and each province. Communities are arranged from the lowest to the highest percentage.

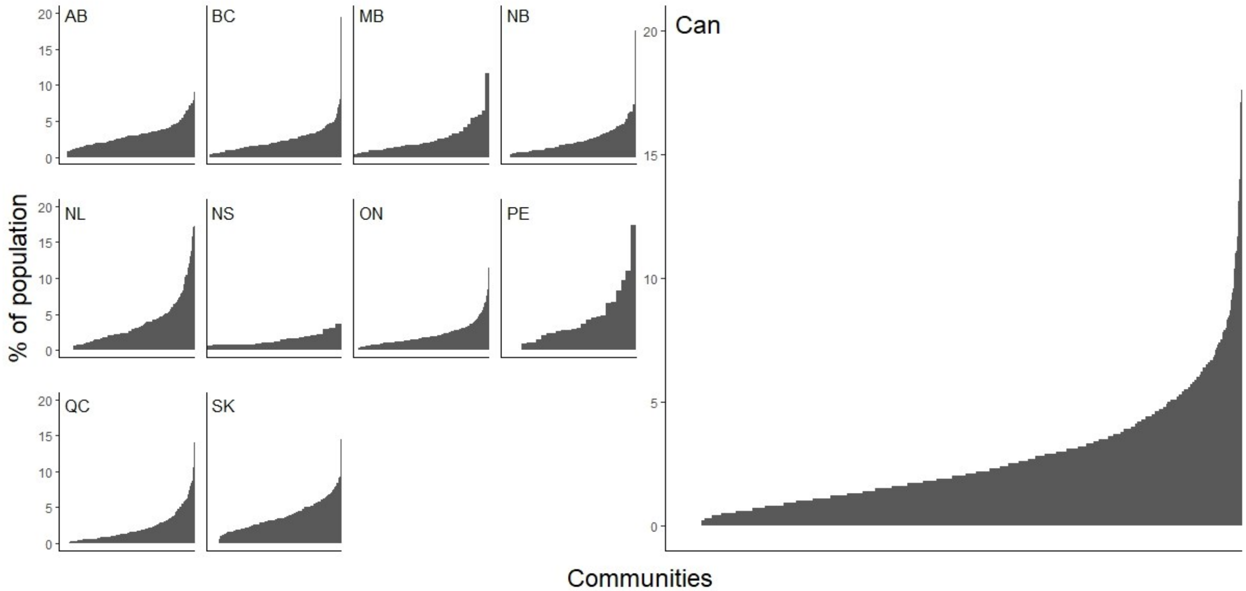


Figure 4.7| Histograms showing the percentage of population employed in natural resources, agriculture, and related production occupations for Canada and each province. Communities are arranged from the lowest to the highest percentage.

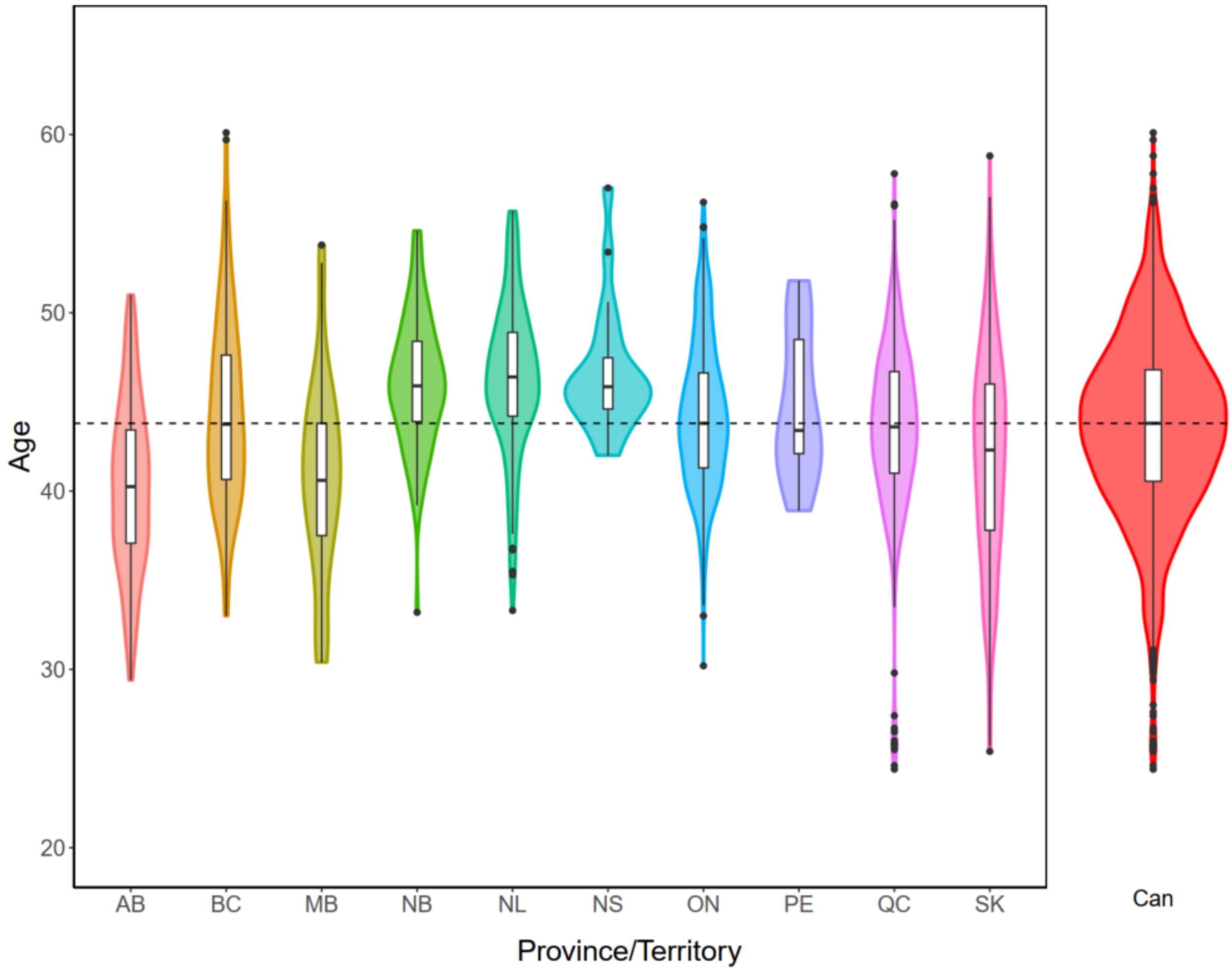


Figure 4.8| Violin graphs showing the age distribution for Canada and each province. Box plots are overlayed over violin graphs to show median, quantiles, and outliers in the data. The dashed line represents the median value for Canada.

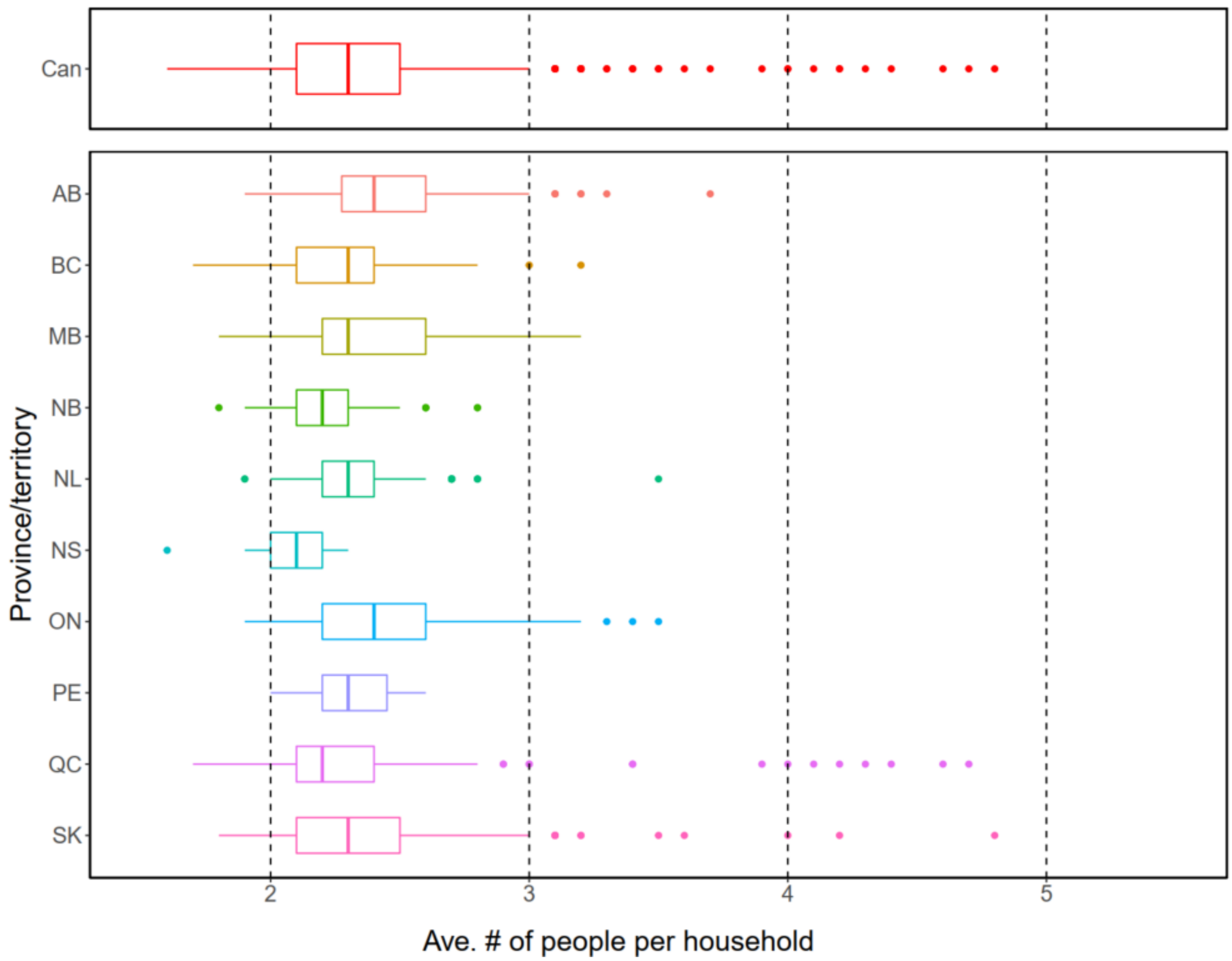


Figure 4.9| Box plots showing the average number of people per household for Canada and each province. The box plots display the median, quantiles, and outliers in the data.

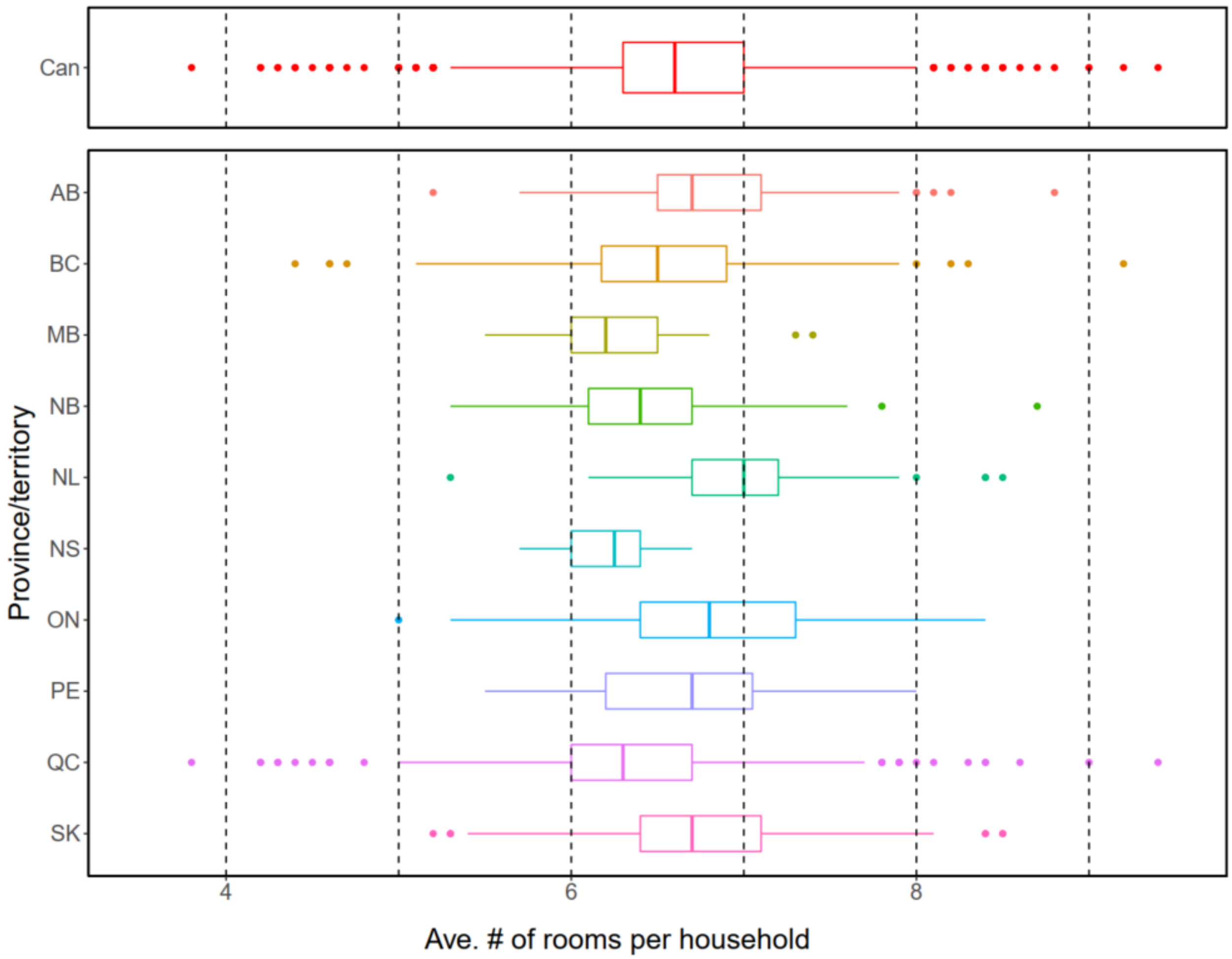


Figure 4.10| Box plots showing the average number of rooms per household for Canada and each province. The box plots display the median, quantiles, and outliers in the data.

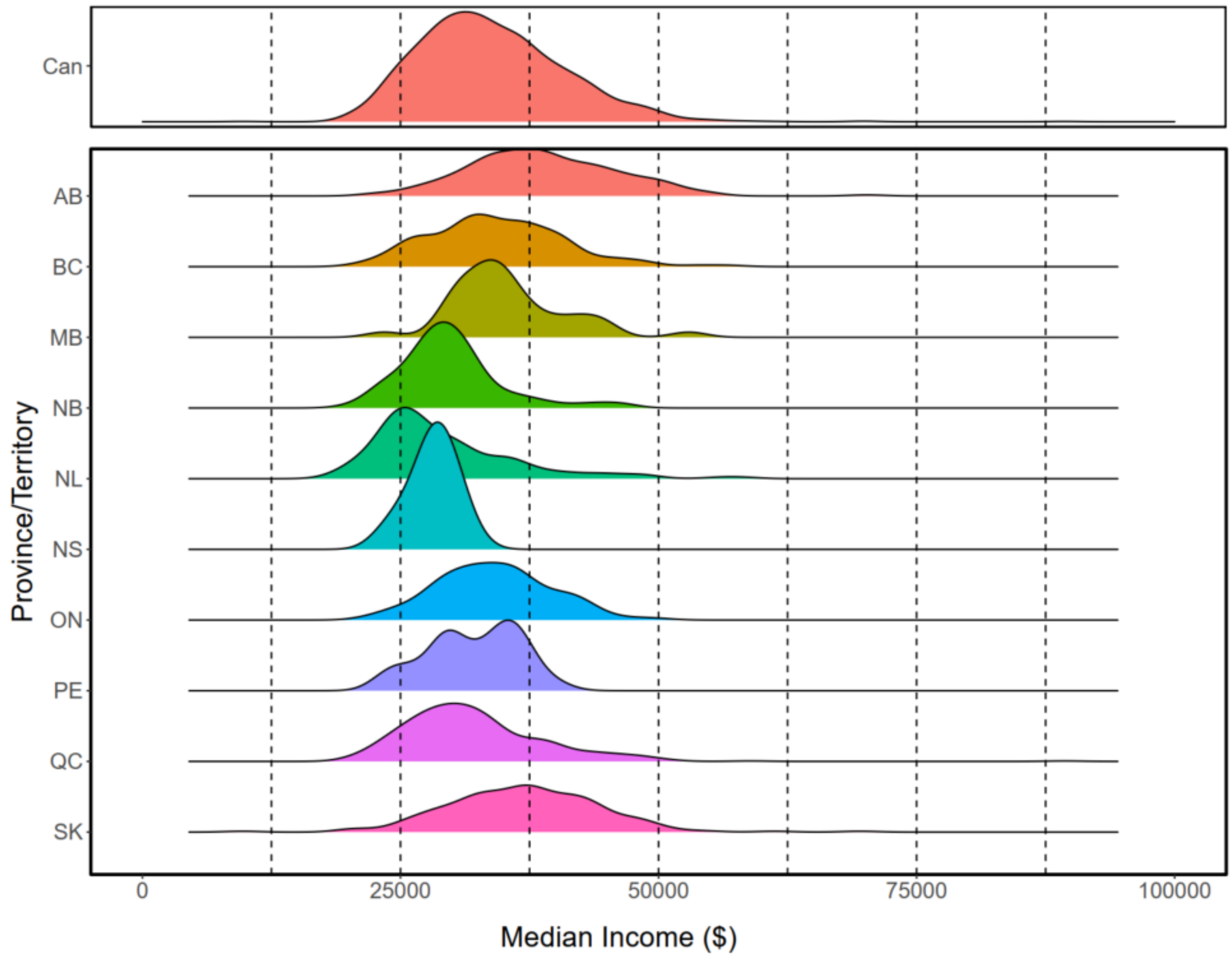


Figure 4.11| Ridgeline plots showing the distribution of median income of recipients for Canada and each province.

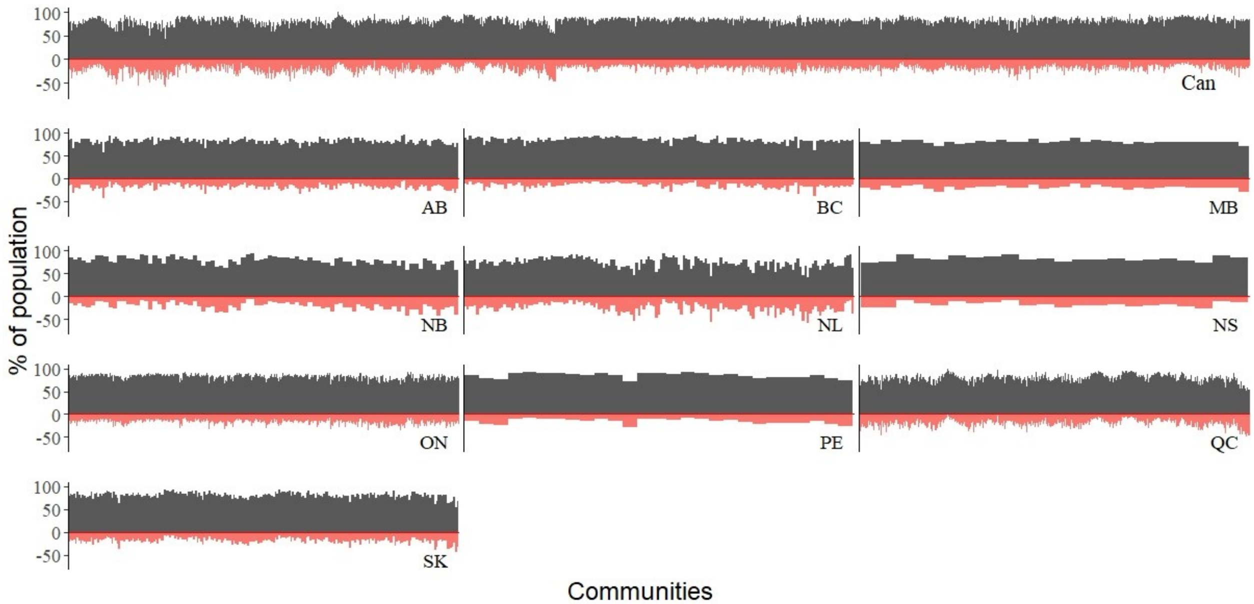


Figure 4.12| Mirror histograms showing the percentage of population with no certificate, diploma, or degree (red) for Canada and each province. This is contrasted with the percentage of population with a certificate, diploma, or degree (grey).

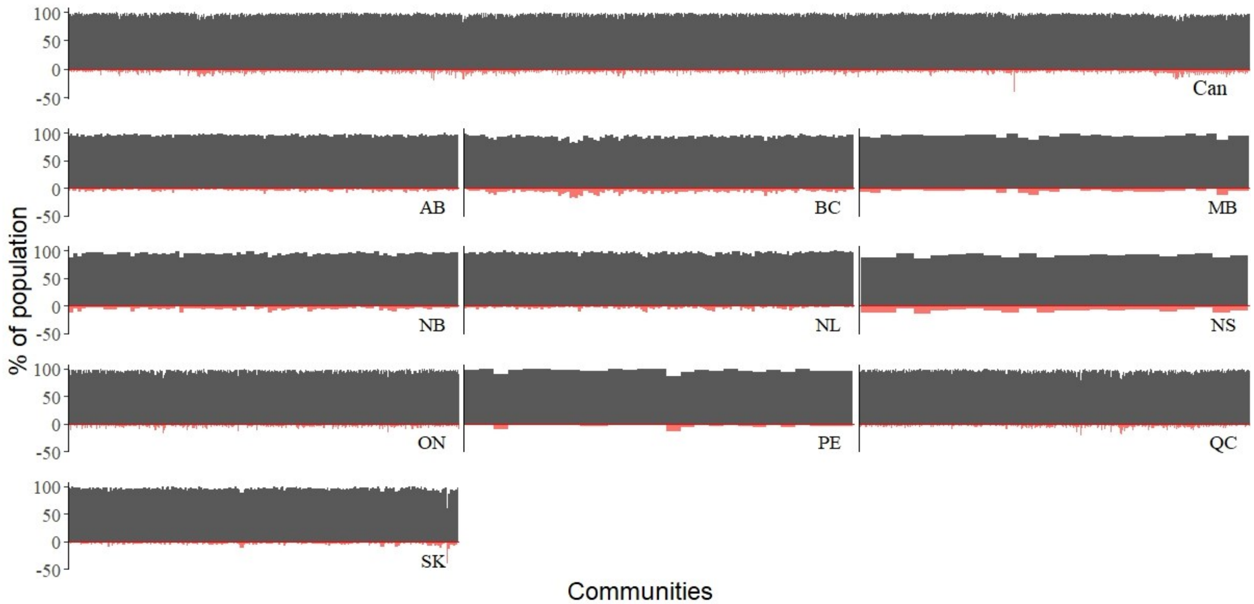


Figure 4.13| Mirror histograms showing the percentage of population with low income based on the low-income cut-offs (red) for Canada and each province. This is contrasted with the percentage of population above the low-income cut-offs (grey).

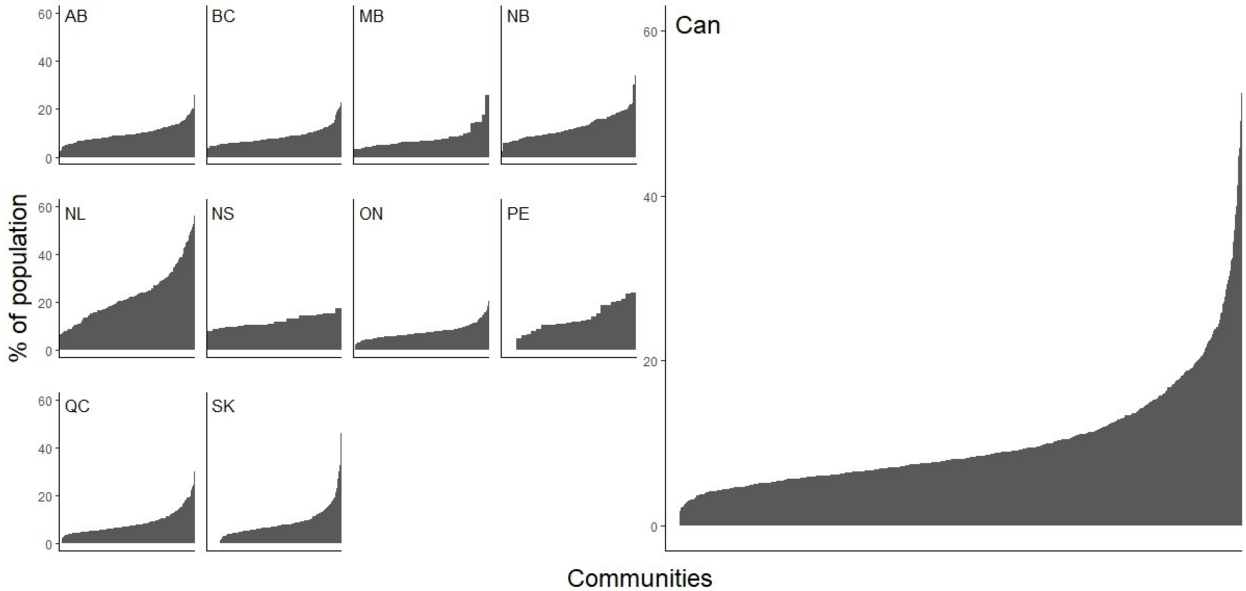


Figure 4.14| Histograms showing the percentage of population that is unemployed for Canada and each province. Communities are arranged from the lowest to the highest percentage.

Chapter 5: Conclusions

5.1 Overview of findings

Evidence-based emission reduction policies are necessary for lowering GHG emissions. A major barrier of developing evidence-based policies is the lack of quantitative understanding of the drivers of emissions. In this thesis, I filled in this knowledge gap and quantified the political governance, socioeconomic, and weather factors that drove subnational GHGs across Canada by (i) exploring how these factors contribute to emissions across provinces, (ii) identifying and comparing those GHG emission factors common to provincial and municipal jurisdictions as well as the factors unique to each jurisdiction, and (iii) investigating how these factors change across communities of differing sizes. My thesis compiled unprecedent GHG emission data across Canadian jurisdictions of different levels and applied sophisticated quantitative methods (e.g., variance partitioning, textual analysis, quantile regression) to address these three questions. In this chapter, I summarize the major findings of my thesis and their policy implications.

In **Chapter 2**, I demonstrated that socioeconomics is the main driver of emissions across Canadian provinces. Political governance alone had only minor and inconsistent effects on emissions. However, I found that governance strongly interacted with socioeconomics in some provinces, suggesting that the impact of governance on GHG emissions is manoeuvred through socioeconomic leverage. It is noted that this strong interaction between political party and socioeconomics varied considerably from province to province, dependent upon the specifics of the regional economy and political party holding office in each province. As a result, political governance itself would have a limited capacity to impose changes in GHGs if the regional economy were not considered. Another important finding of this chapter is that better dispersion of energy efficient technologies across society is an effective means to limit emissions.

In **Chapter 3**, I showed that socioeconomic factors affected household emission at both provincial and city jurisdictions regardless of the sources of GHG, e.g., from fossil fuel or non-fossil fuel energy consumption. Political governance was found to only correlate with household emission variation at the city jurisdictional level. Overall, the drivers of household GHG emissions changed across jurisdictions and energy sources. This leads me to conclude that incorporating local, energy specific policies into subnational and national emission reduction strategies is necessary for future household emission reductions.

In **Chapter 4**, I indicated that affluence and population were the most significant factors affecting community emissions, but their effects varied across community GHG quantiles. The effect of affluence on emissions increased from low to high GHG emission community quantiles, while the effect of population decreased (i.e., low to high quantiles). In general, factors affecting GHGs changed across community emission quantiles. Poverty was associated with GHG increases at the national level for all quantiles, suggesting that policies targeting economic inequality may lower community GHGs while providing additional societal benefits. I concluded that policies aiming to reduce community emissions, with specific attention focused on variation in community affluence and population, must be based on individual communities to be effective.

5.2 Key contributions

My thesis has provided studies that decompose the drivers of GHG emissions. One of the main contributions is the quantification of the effect of political governance on emission variation relative to other drivers of GHGs. This quantification is much needed for understanding and identifying the sources of GHG emission (Carter et al., 2018; Hu et al., 2021). In Chapter 2, I quantify the extent that changes in provincial political parties holding office have on provincial GHG variation in relation to socioeconomic and weather factors. In a North American context, the quantification of differing political parties to affect emissions is limited. Upon my review of the global literature surrounding party politics and emissions, I found only one article that attempts to quantify the effect of differing Canadian political parties on air pollution (see McKitrick, 2006). This is in stark contrast with political researchers in Europe where the quantification of the effect of political parties holding office on various societal and environmental outcomes is much more thoroughly explored and openly discussed. For example, the Manifesto Project has been providing European political party data to researchers and producing research articles/reports for comparing the effects of political parties on different societal and environmental outcomes for decades (Manifesto Project, 2022). Questioning the role that party politics plays in determining environmental outcomes is required if we are going to improve upon our current system of governance (Hu et al., 2021). As such, the quantitative decomposition of the effects of provincial political parties, socioeconomics, and weather on provincial GHGs can enhance our ability to develop effective future climate change adaptation/mitigation policies through a better-informed understanding of the political economy of subnational emissions and how weather drives emission releases on a regional scale.

In Chapter 3, I bring two further contributions to climate change research. First, I estimate and include three political variables into my analyses: the placement of city councils and provincial legislatures on an environmental-developmental policy spectrum, the relative environmental sentiment of city councils and provincial legislatures, and the relative developmental sentiment of city councils and provincial legislatures. This was done by converting city council minutes and provincial Hansards to textual data then estimating the variables using established textual analysis methodologies. Using such political variables obtained from textual data as independent factors in a regression, as far as I could find, has never been done before. This is an important contribution because our ability to manage and analyze big data, including textual data, is becoming evermore accessible (Whang, 2018). Applying such methods to decades of political discussions or similar has a high potential for a better understanding of the democratic process and reforms necessary to make the process more efficient in the modern world.

For my second key contribution from Chapter 3, I explore how the drivers of household emissions change across two different vertical scales of subnational jurisdictions: from the city to the provincial jurisdiction. Such explorations are still limited but much needed in climate change adaptation research (Fuhr et al., 2018; Hu et al., 2021). To better integrate climate change policies across jurisdictions, both vertically and horizontally, we must understand how the drivers of emissions change across these jurisdictions (Clar, 2019). Understanding these drivers will yield the potential to create better integrated, targeted policies that can simultaneously allocate resources more efficiently across society while also providing the necessary autonomy to community decision makers to initiate effective emission reduction actions at the local scale.

Recognizing the differences between communities, Chapter 4 uses quantile regression (QR) to explore the nuances of community level emissions in finer detail. QR has been used in emission research and similarly related fields (Adebayo et al., 2022; Alotaibi & Alajlan, 2021; Chen et al., 2019; Cheng et al., 2021; Kaza, 2010; Xie et al., 2021), but the application of QR to modeling the drivers of community emissions is novel and provides insights to guide community emission policy creation. I have done this using differing community sizes across Canada (based on total and per capita consumption-based emissions per community), allowing for a more nuanced interpretation of what drives emissions across these communities. This can impart larger governmental jurisdictions, like provincial or national governments, with details to allocate emission reduction resources across communities more efficiently. In addition, QR reveals potential policy solutions that are universal across all communities. For example, my research revealed that economic poverty is associated with increased emissions in communities of all sizes across Canada. This suggests that policies targeting community income inequality could lower community GHG emissions together with many other societal benefits (Gaitán-Rossi & Velázquez Guadarrama, 2021; Hallegatte & Rozenberg, 2017; Kerr et al., 2017; Thompson et al., 2014). Quantifying the benefits from emission reductions attributed to lowering poverty rates could offer additional incentives to establish and support poverty reduction initiatives.

Since my thesis uses federal emissions data presented to the UNFCCC in Chapter 2 (Environment and Climate Change Canada, 2021), and that UN publications are cited throughout this thesis, it is also important for me to briefly discuss how my thesis contributes to several of the UN's Sustainable Development Goals (SDGs; UN, 2022). The most notable of these are SDG 13 (climate action) and SDG 7 (affordable and clean energy). The focus of my research is to quantify the drivers of subnational emissions. Some of my key findings throughout the thesis are in support of transitioning energy produced from fossil fuels, particularly electricity, to non-fossil fuel sources. Additionally, I have discussed the necessity of making energy efficient technologies readily available to transition society to cleaner sources of energy or reduce energy usage. Furthermore, my thesis touches on SDG 10 (reduced inequalities) by linking the potential for poverty reduction initiatives to lower community emissions in Chapter 4, and SDG 11 (sustainable cities and communities) through my ample discussions of the need to transition communities to more environmentally friendly energy sources, energy efficient technologies, and behavioral changes in Chapters 2, 3, and 4. My thesis also contributes to SDG 12 (responsible consumption and production), with consistent discussion throughout my thesis describing instances that we need to both produce and consume energy more responsibly; and SDG 16 (peace, justice, and strong institutions) with my research having a strong element of assigning political accountability for our current climate crisis and delivering suggestions to help address these concerns.

5.3 Limitations and future research opportunities

Climate change is a wicked problem, meaning that there is no clear solution to solve this problem (Grundmann, 2016; Levin et al., 2012). The best we can do is break-up the climate change problem into smaller, workable problems. However, many of these smaller problems, such as adapting urban areas to a changing climate (Kirby, 2018), addressing climate related biodiversity loss (Sharman & Mlambo, 2012), or dealing with water security concerns (Hargrove & Heyman, 2020), are, in and of themselves, difficult to address. Notwithstanding, we still must work together to do the best we can at figuring out how to effectively navigate our global climate emergency. With my own humble acceptance of the realities of mitigating and adapting to a changing climate, I have provided several contributions to inform future climate change policies. I recognize that these contributions are by no means comprehensive, but to do so would be impossible. With that said, I have presented some of the limitations of my thesis and opportunities for future research below.

Throughout my thesis, I used several different methods of measuring political governance, but the concept of what governance is and how to measure it is more complicated than political party in office or the discourse happening in provincial legislatures or city council meetings (Colebatch, 2014). My research has given much insight into how subnational governments interact with GHGs, but further research is still needed. I used what data and methods were available to me given the scarcity of time and resources but there are potentially more angles one can quantify a governmental variable, providing further insights. This may include measuring governance over different timeframes, across different jurisdictions (both vertically and horizontally), or employing different aspects of effective governance such as measures of corruption, to name only a few (Hu et al., 2021). The focus of my research was on subnational jurisdictions (i.e., provinces and municipalities) to compare how the drivers of emissions change across these boundaries. It is meant to help clarify limited information on how emissions change across these boundaries (Hsu et al., 2019; Hultman et al., 2020). I mention on several occasions throughout my thesis that integration across boundaries, including national and international levels, is vital. Future research could design similar studies as to my third chapter but involve three or more vertical levels of jurisdictional governance (e.g., municipal, provincial, national, supranational, etc.) to provide additional insights. I would also recommend more homogenized data across jurisdictions. Census boundaries categories, for example, are defined by the province, not nationally, so each province defines census subdivisions (CSD) and similar differently (Statistics Canada, 2019). Better homogenization of boundary area definitions across provinces, such as CSDs, would help make transboundary comparisons easier and more meaningful. Also, GHG data is still limited, especially at the community level. Having the availability of longer temporal data over more communities would be helpful. Furthermore, one could better explore the effects of governance on subnational emissions by quantifying different aspects of good governance (e.g., level of corruption) and its effects on specific energy sources or economic sectors of society.

In my third chapter, I did use some decomposition of emissions in my analyses by looking at household emissions according to energy source (i.e., electricity, natural gas, and petrol). This decomposition was very enlightening. I believe, given data availability, similar decompositions would be quite fruitful. Furthermore, my third chapter also examined a specific sector of GHGs, residential household emissions. With additional resources and time, it would be useful to explore my research from the perspective of multiple economic sectors (e.g., industry, commercial, transportation, etc.). Similarly, Chapter 2 uses production-based emissions while Chapters 3 and 4 use consumption-based emissions. Further decomposition of both forms of carbon accounting is likely to reveal additional insights into the production-consumption cycles that produce GHGs as by-products.

My thesis is an outcome of interdisciplinary studies, though the focus is largely on the effects of political governance, socioeconomics, and weather. I acknowledge that there is still room to improve and to be more inclusive, including but not limited to the areas of environmental sociology, resource economics, atmospheric science, political science, and modeling. I synthesized the necessary information to complete this thesis to the best of my ability, but I also recognize that I still require a deeper understanding of many topics related to my research, from environmental law to climate justice to more detailed knowledge about how large international organizations like the UN function.

In reflecting on my own personal history and what drove me to complete a PhD thesis, I also recognize that there are many potential biases in my research. I have been as objective as possible in interpreting the results and discussing their policy implications. It is in these interpretations and discussions that my personal biases may have been presented. I was born and largely raised in Alberta, a predominant producer of global hydrocarbons with a strong sociocultural, economic, and political basis that is a by-product of and strongly supports oil and gas development. Growing up in such a province means I likely have subconscious biases either for or against hydrocarbon development. However, to conclude my PhD program I have stayed as objective as possible to present my thesis.

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APPENDIX A: CHAPTER FOUR PROVINCIAL QUANTILE REGRESSION RESULTS

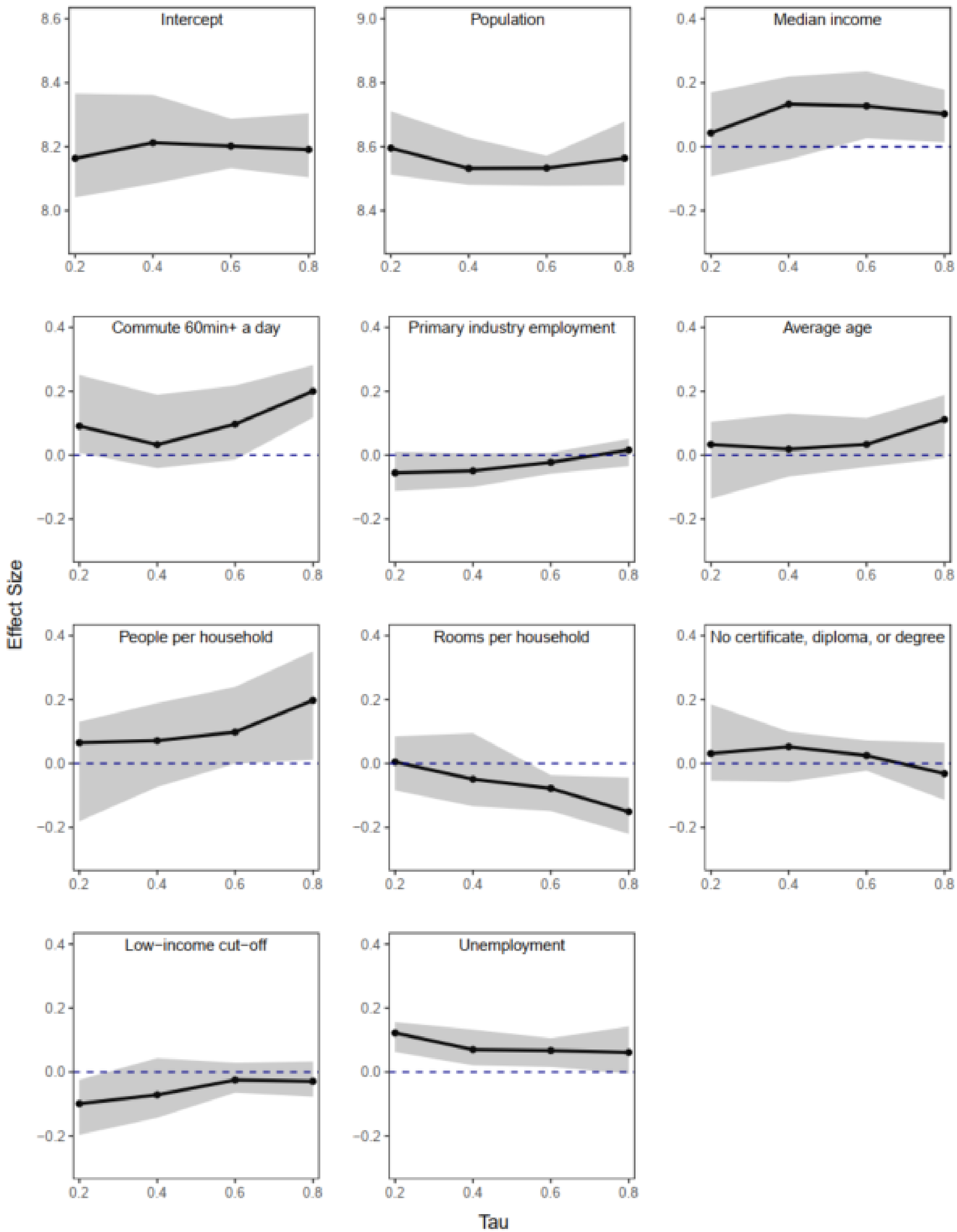
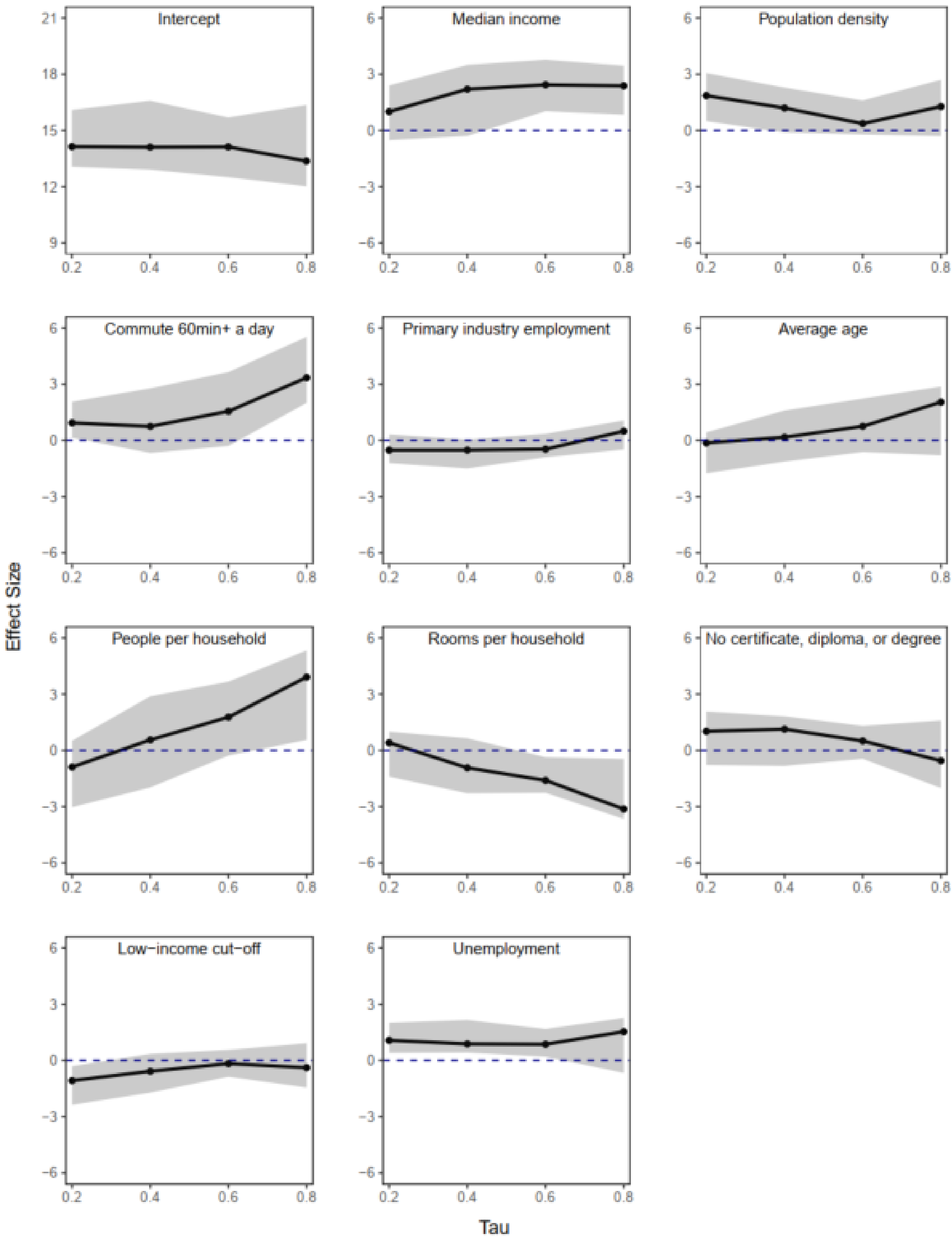
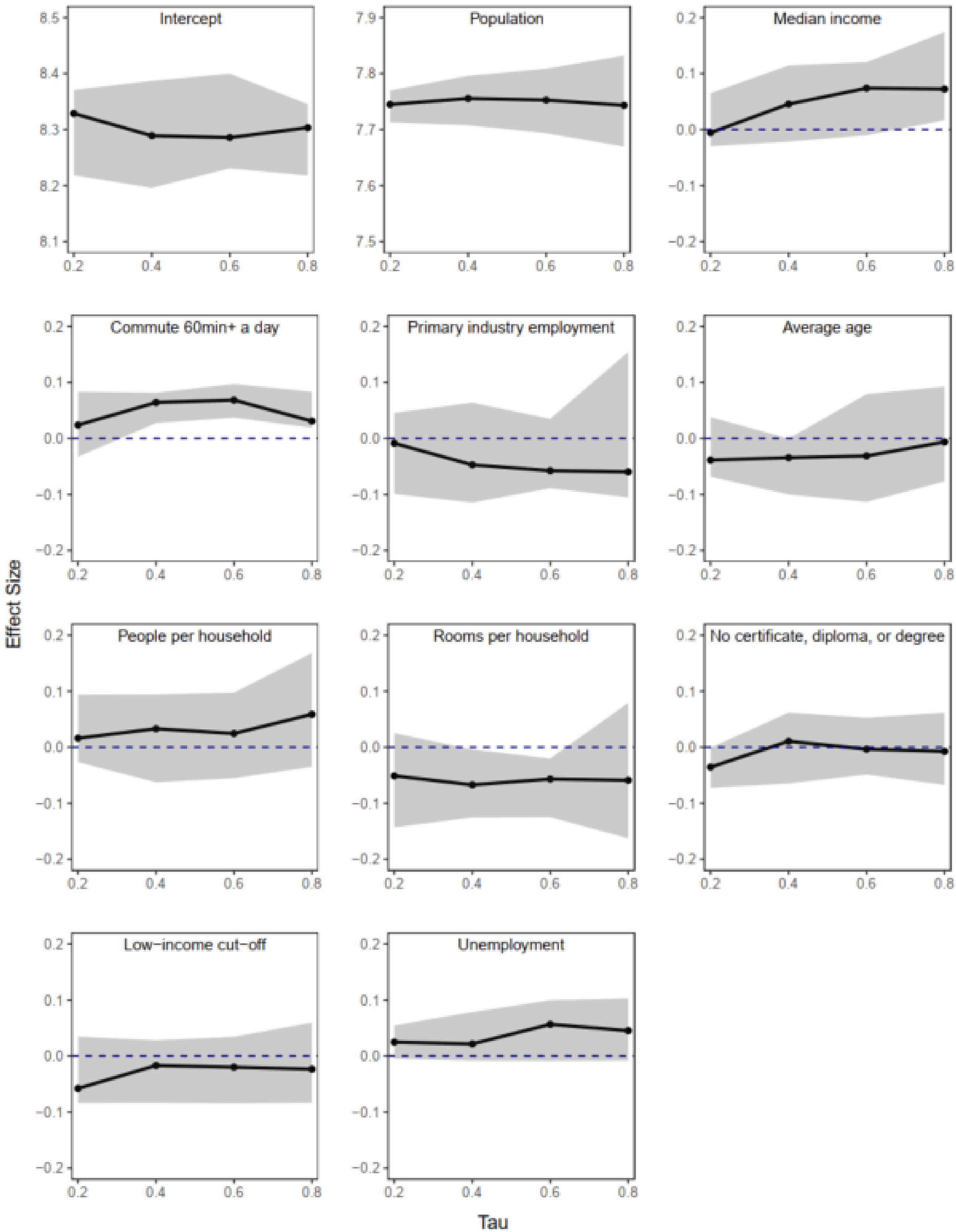


Figure A.1| QR results for total community CO_2 emissions in Alberta where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



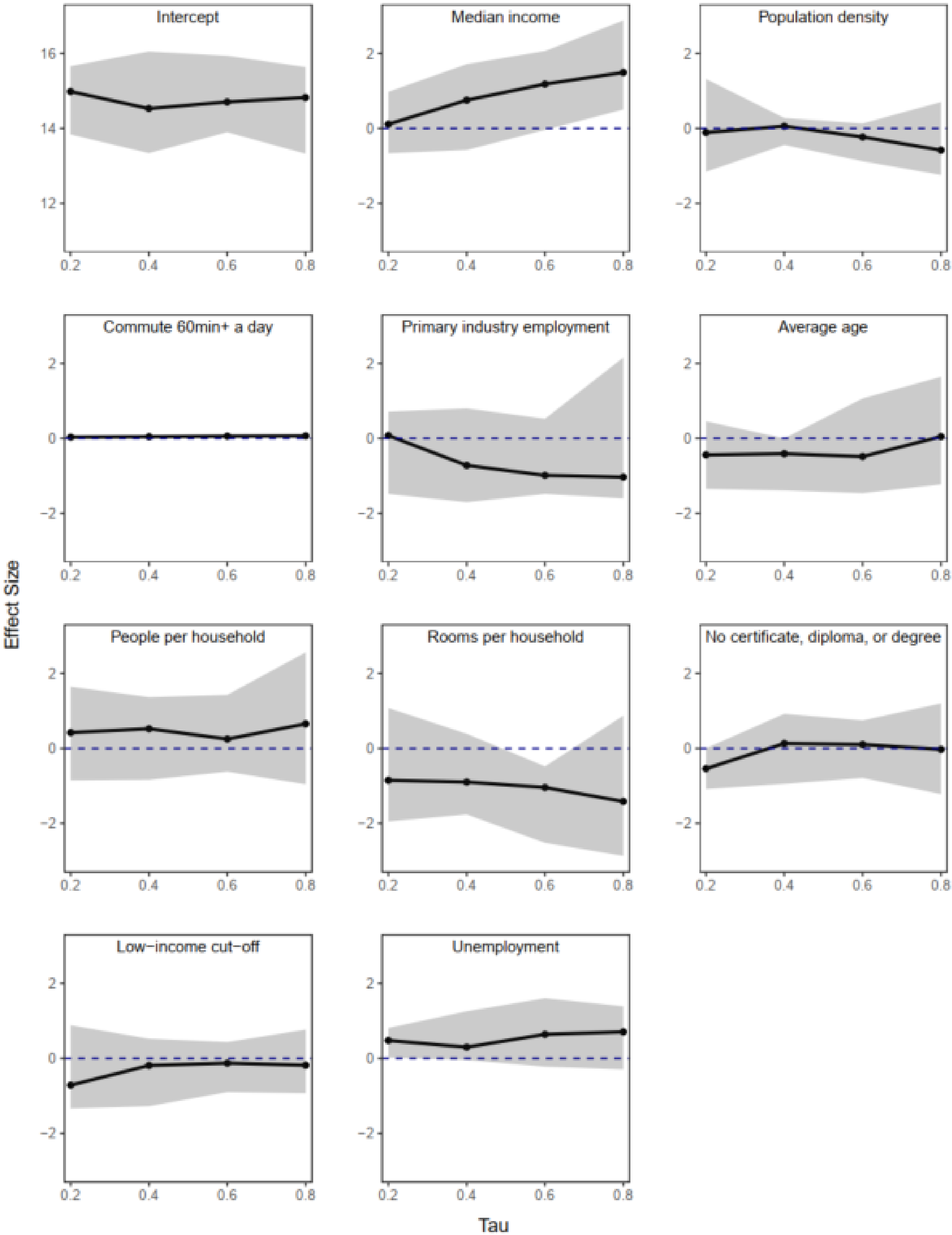
Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.2| QR results for per capita community CO_2 emissions in Alberta where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



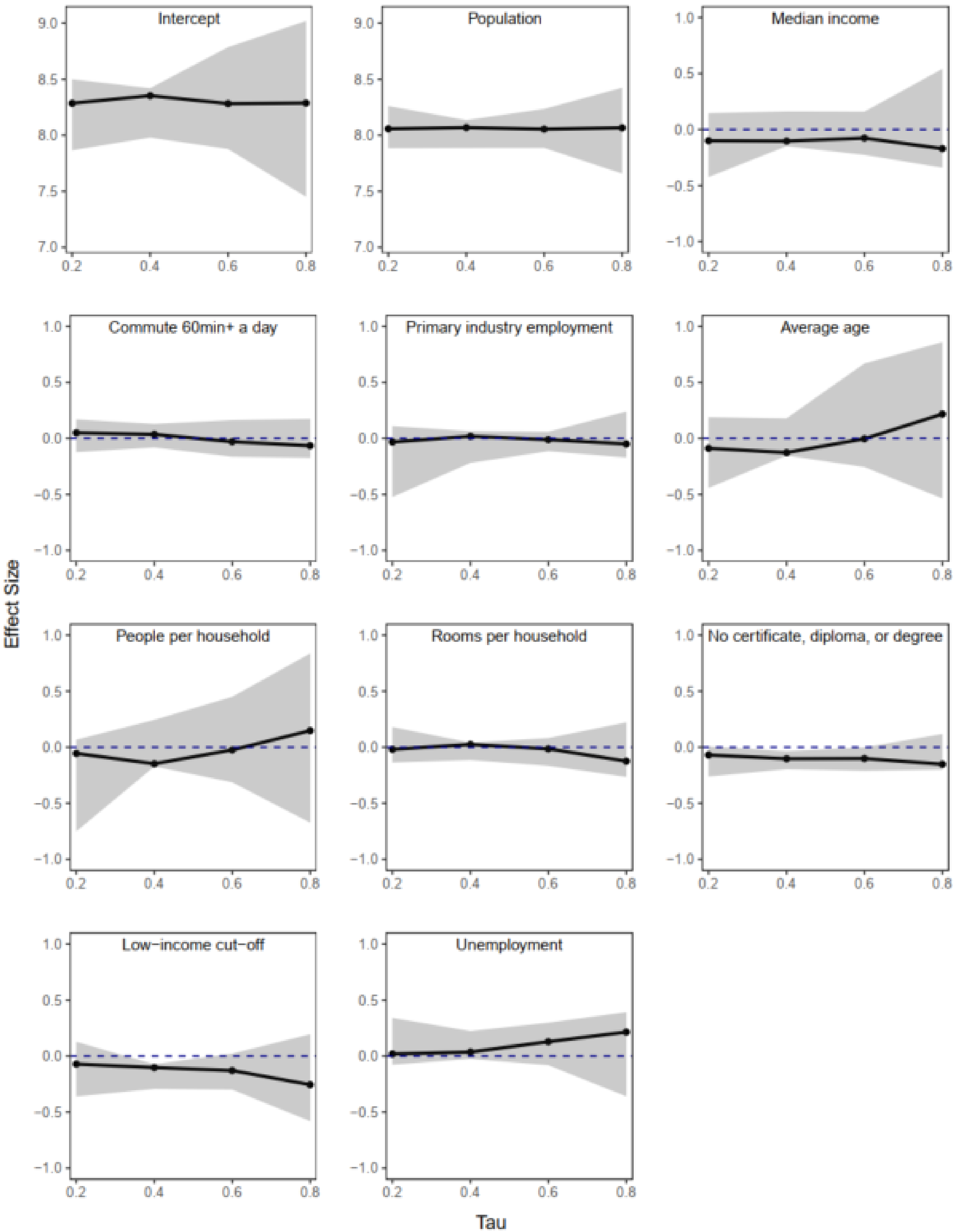
Intercept
Population
Median income
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.3| QR results for total community CO_2 emissions in British Columbia where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



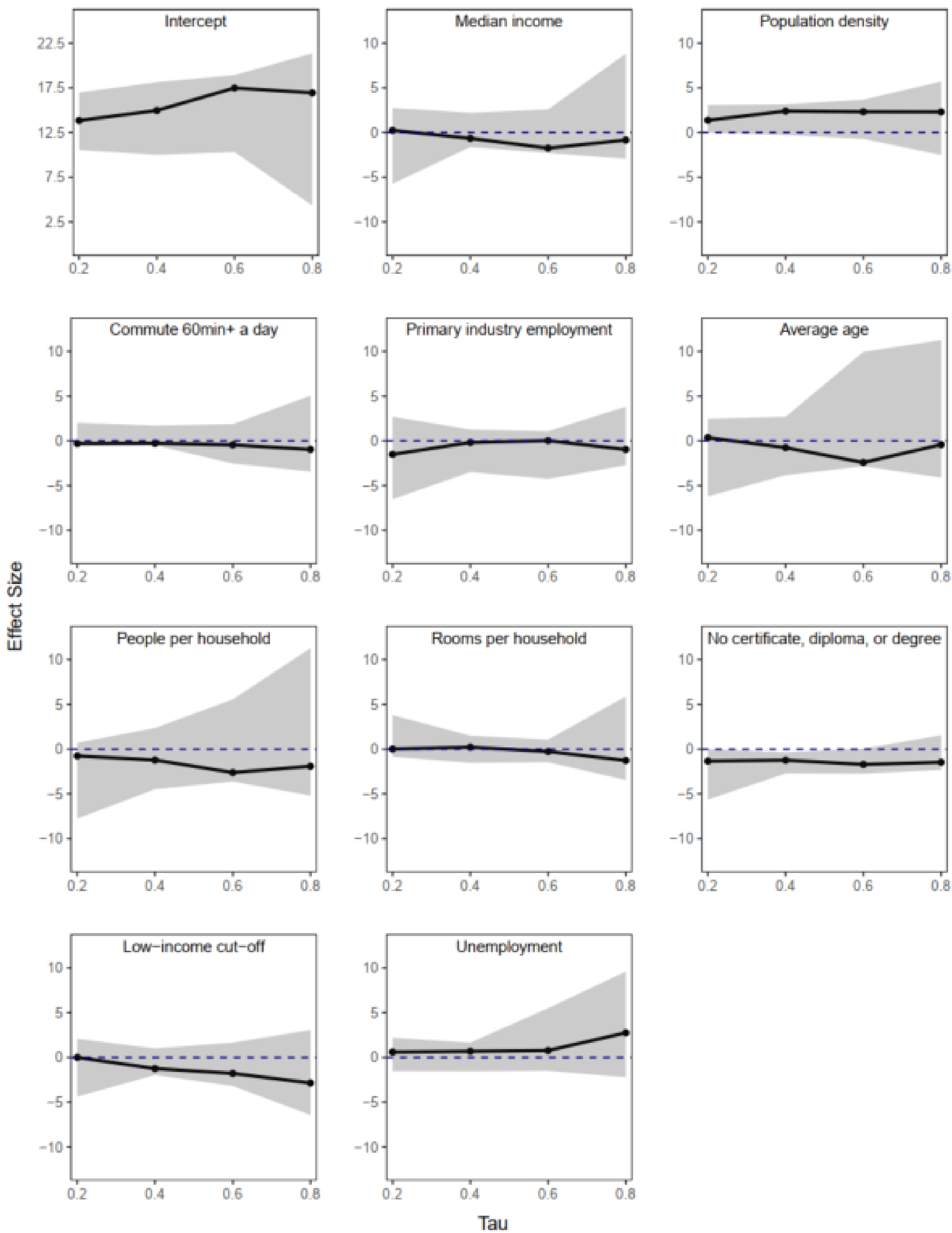
Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.4| QR results for per capita community CO_2 emissions in British Columbia where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



Intercept
Population
Median income
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.5| QR results for total community CO_2 emissions in Manitoba where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.6| QR results for per capita community CO_2 emissions in Manitoba where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

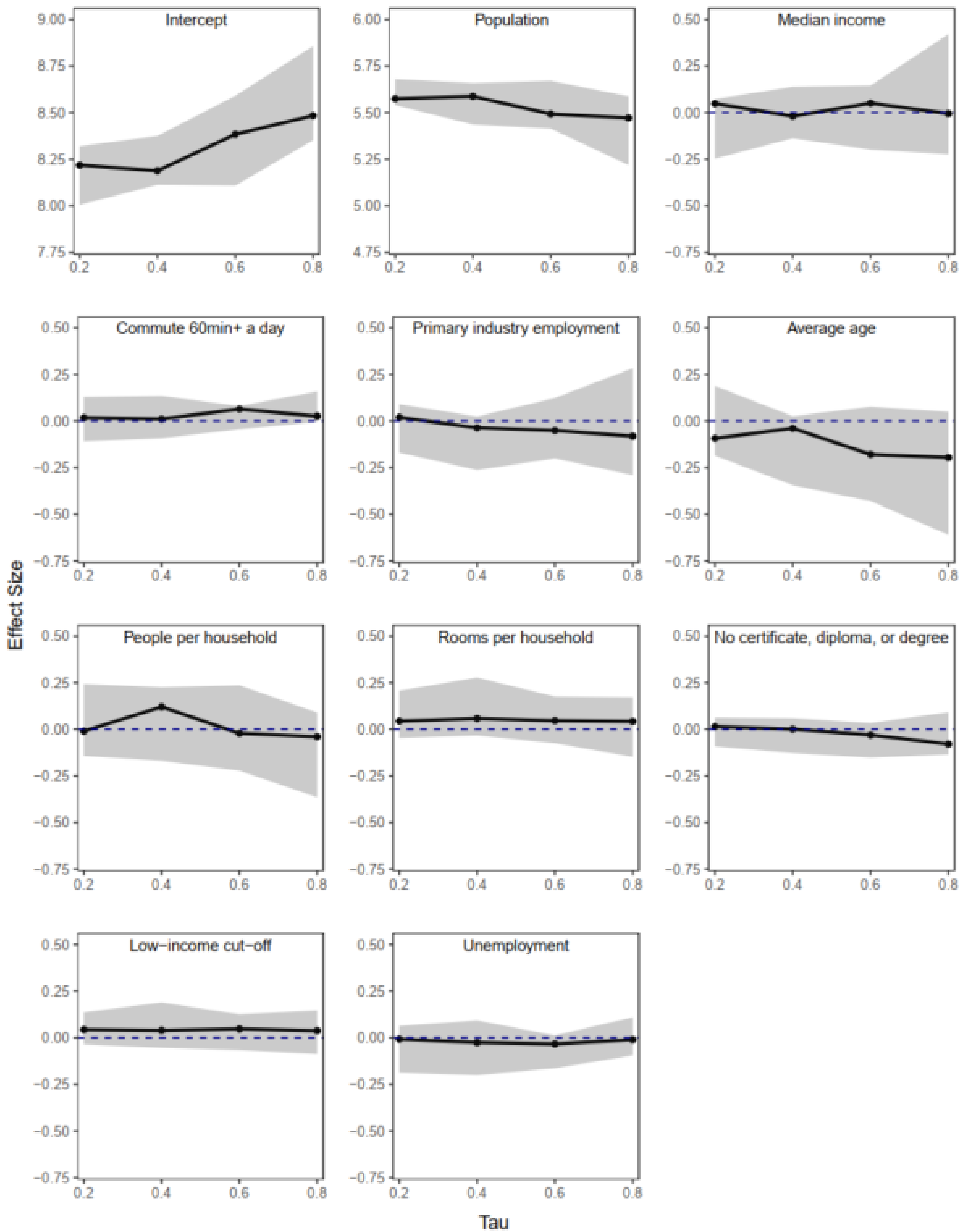

Intercept
Population
Median income
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.7| QR results for total community CO_2 emissions in New Brunswick where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

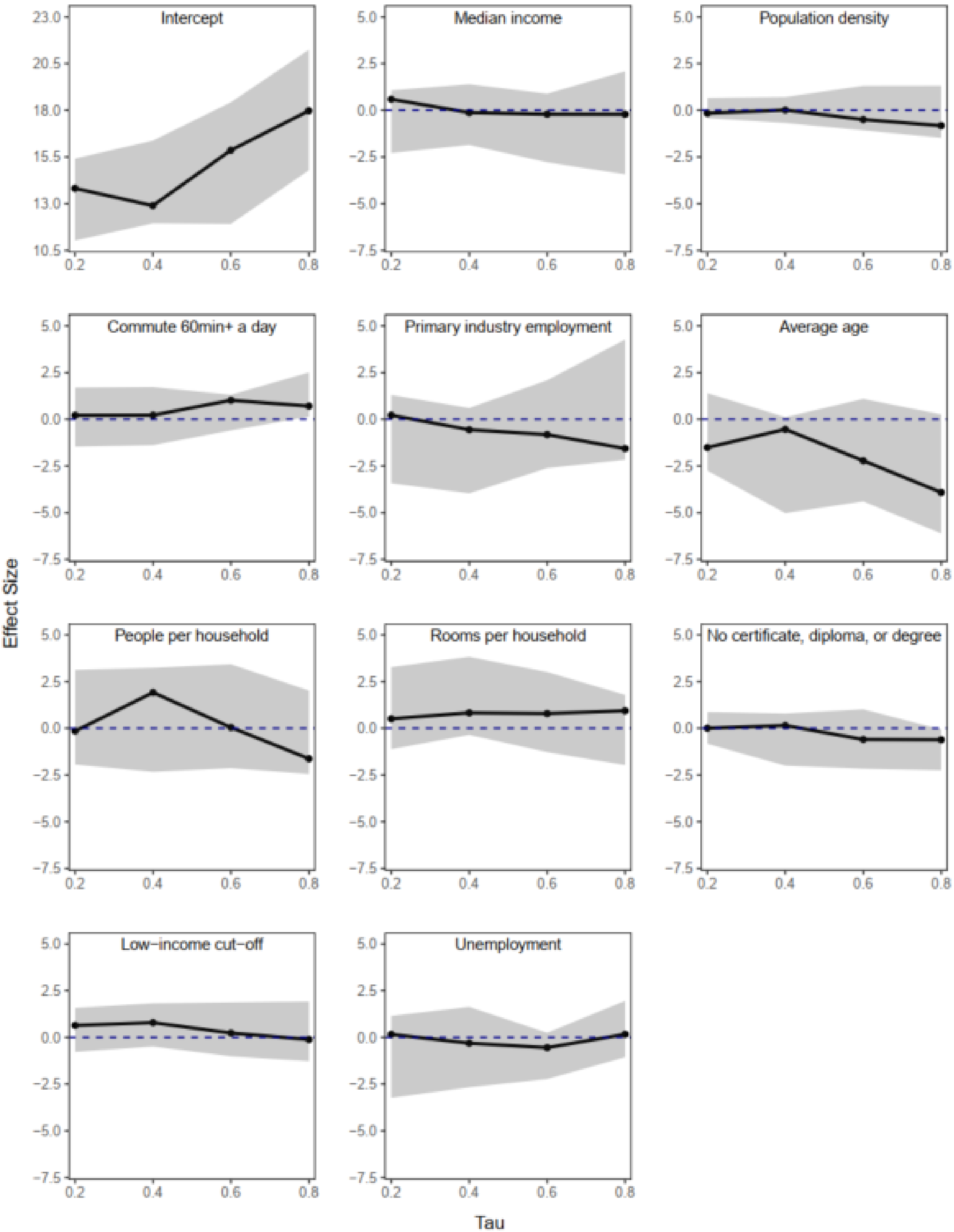
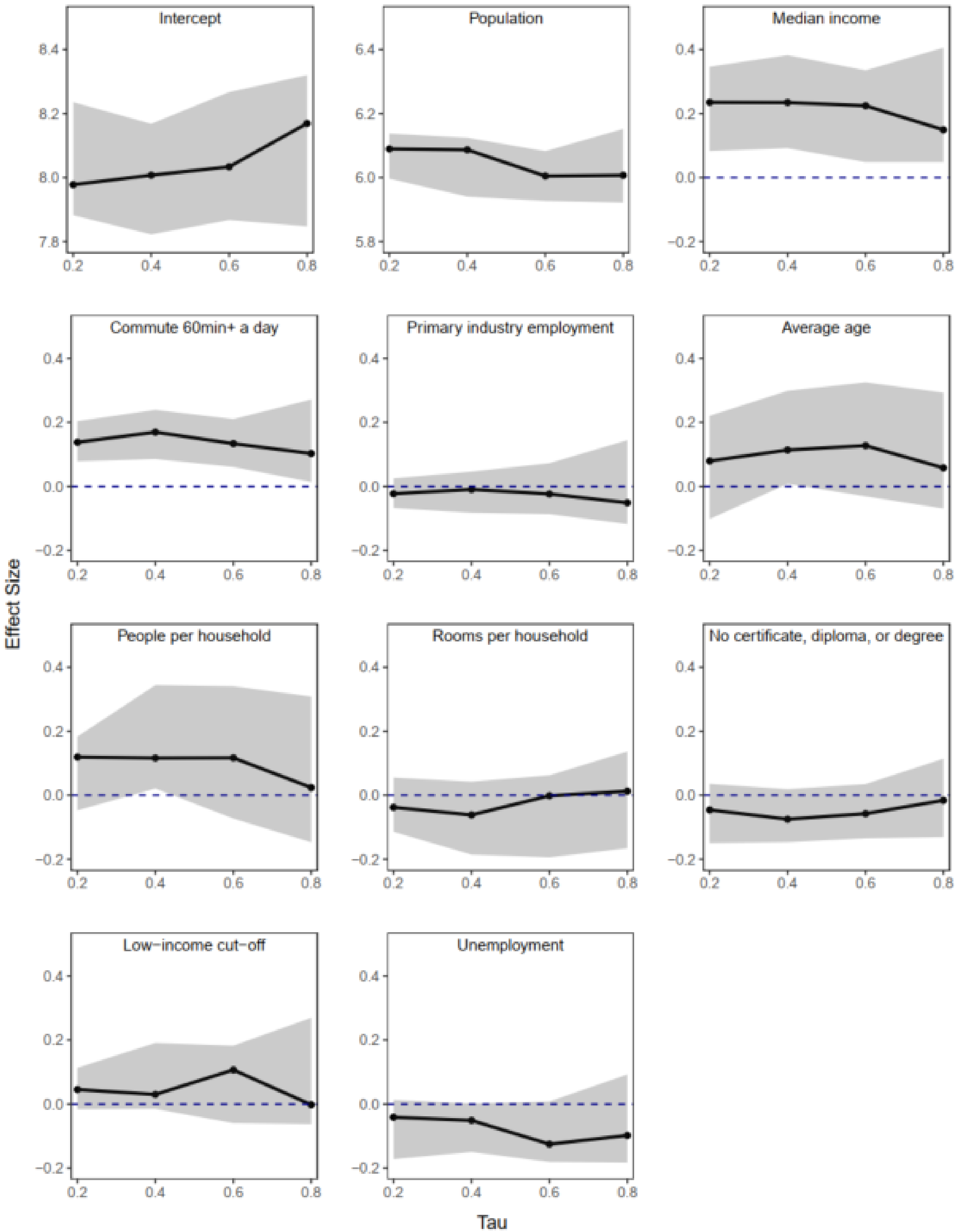
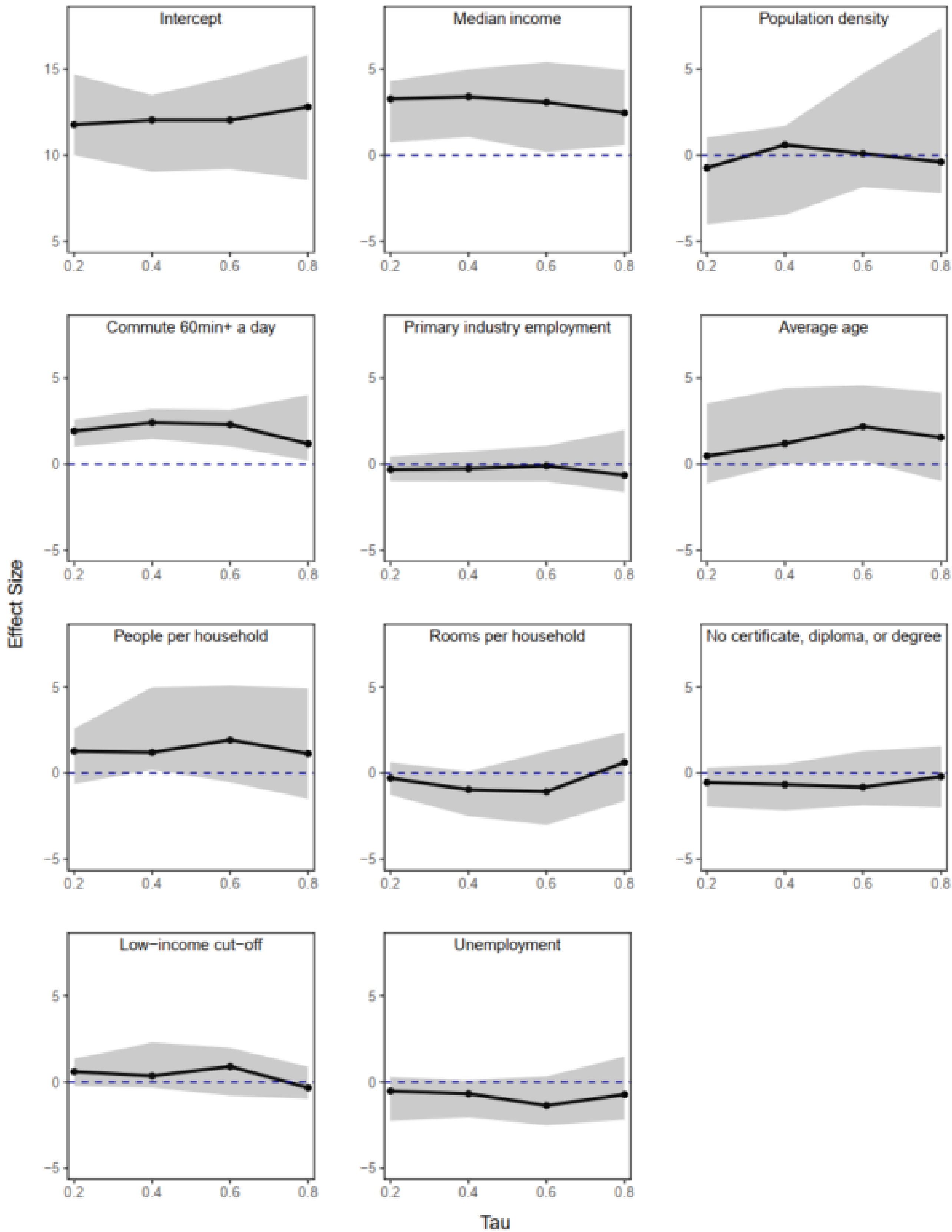

Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.8| QR results for per capita community CO_2 emissions in New Brunswick where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



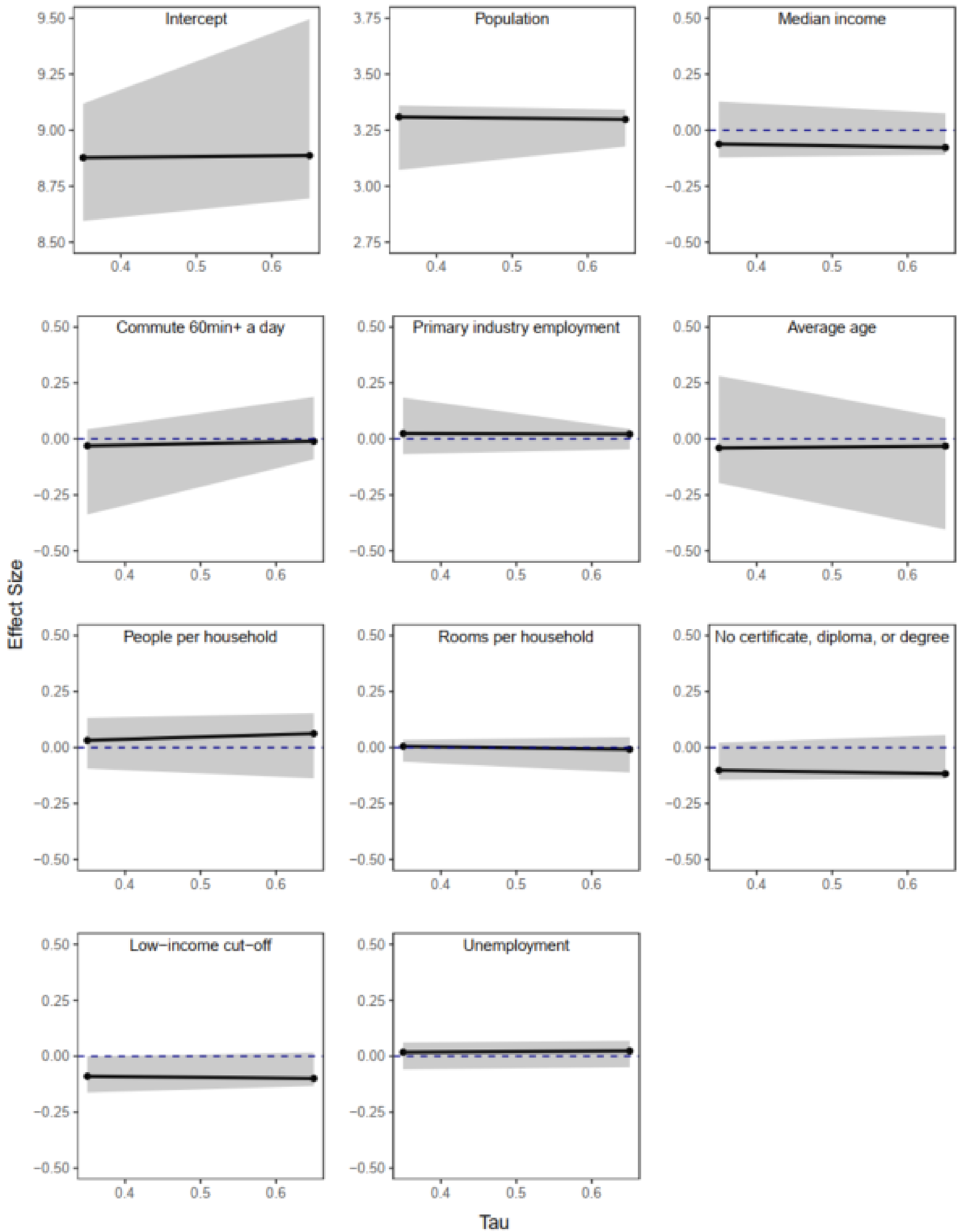
Intercept
Population
Median income
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.9| QR results for total community CO_2 emissions in Newfoundland and Labrador where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.10| QR results for per capita community CO_2 emissions in Newfoundland and Labrador where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



Intercept
Population
Median income
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.11| QR results for total community CO_2 emissions in Nova Scotia where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

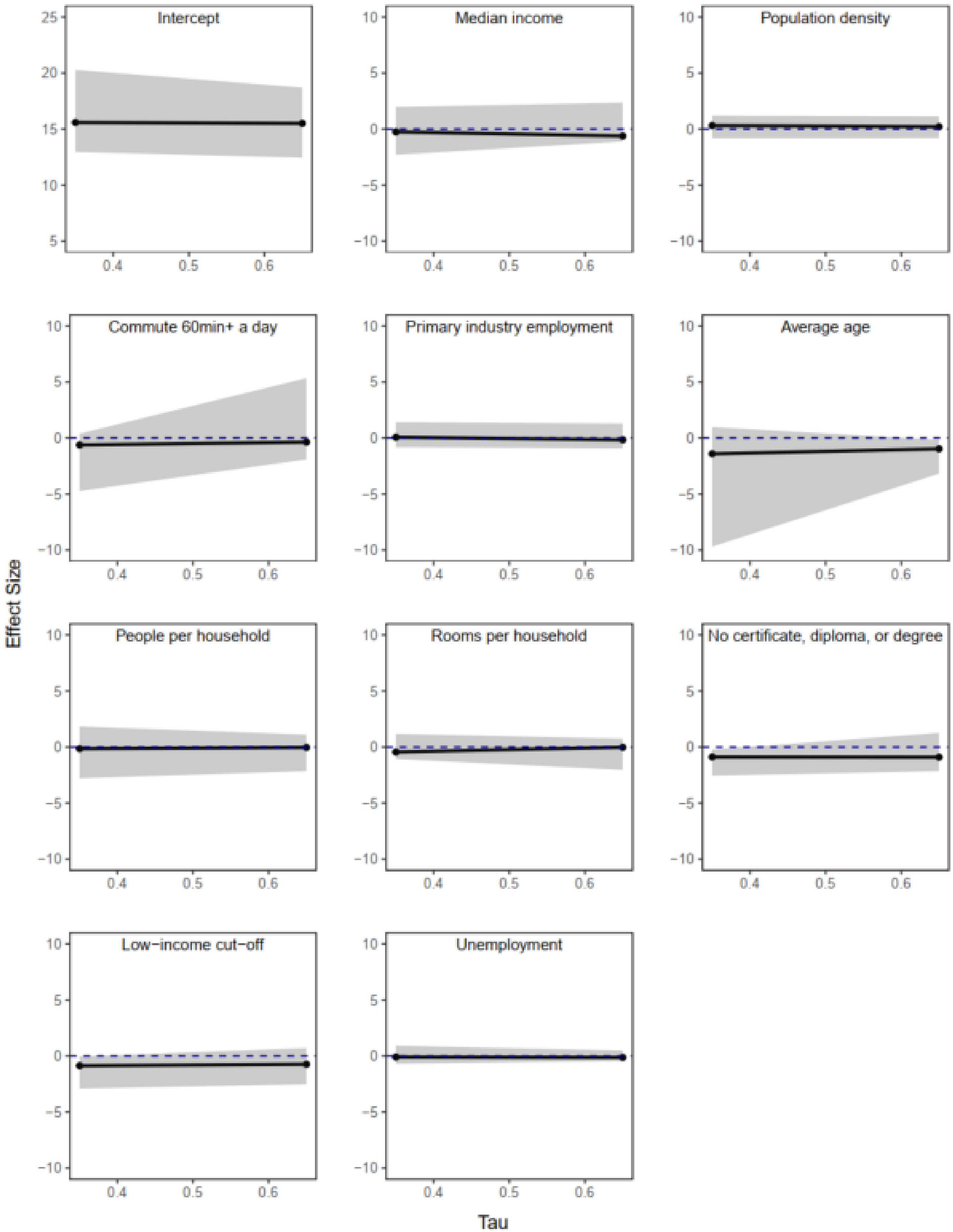
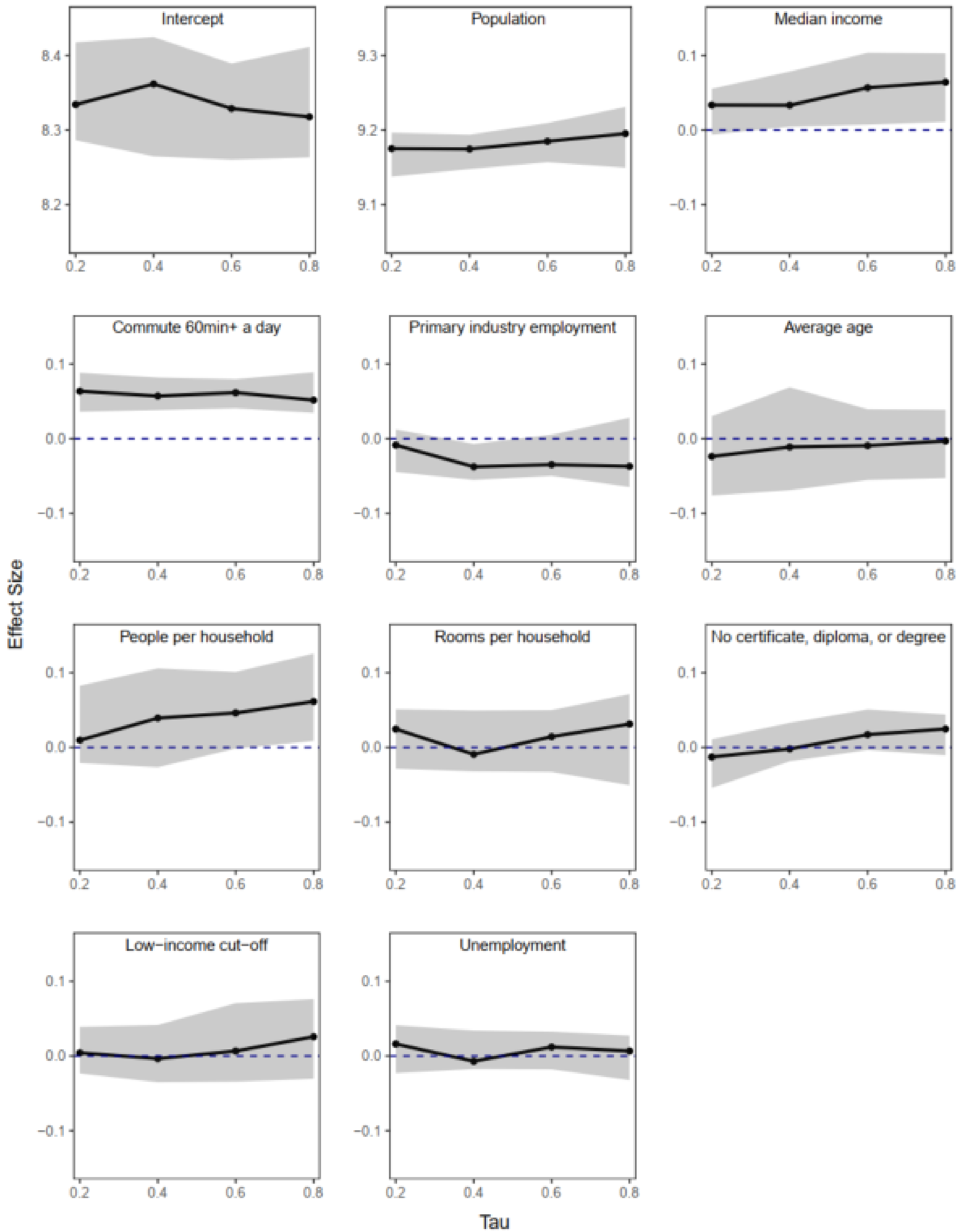

Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.12| QR results for per capita community CO_2 emissions in Nova Scotia where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



Intercept
Population
Median income
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.13| QR results for total community CO_2 emissions in Ontario where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

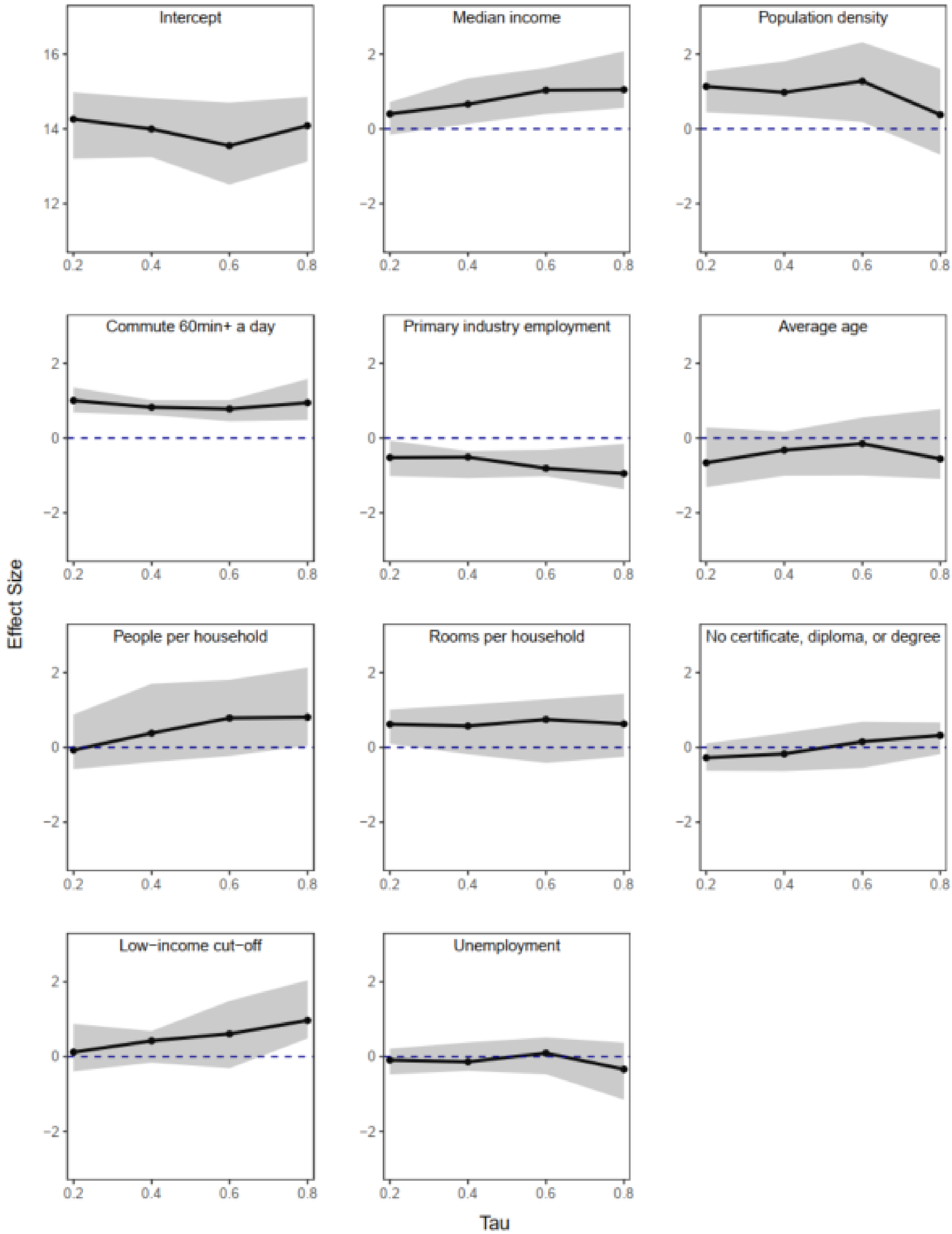

Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.14| QR results for per capita community CO_2 emissions in Ontario where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

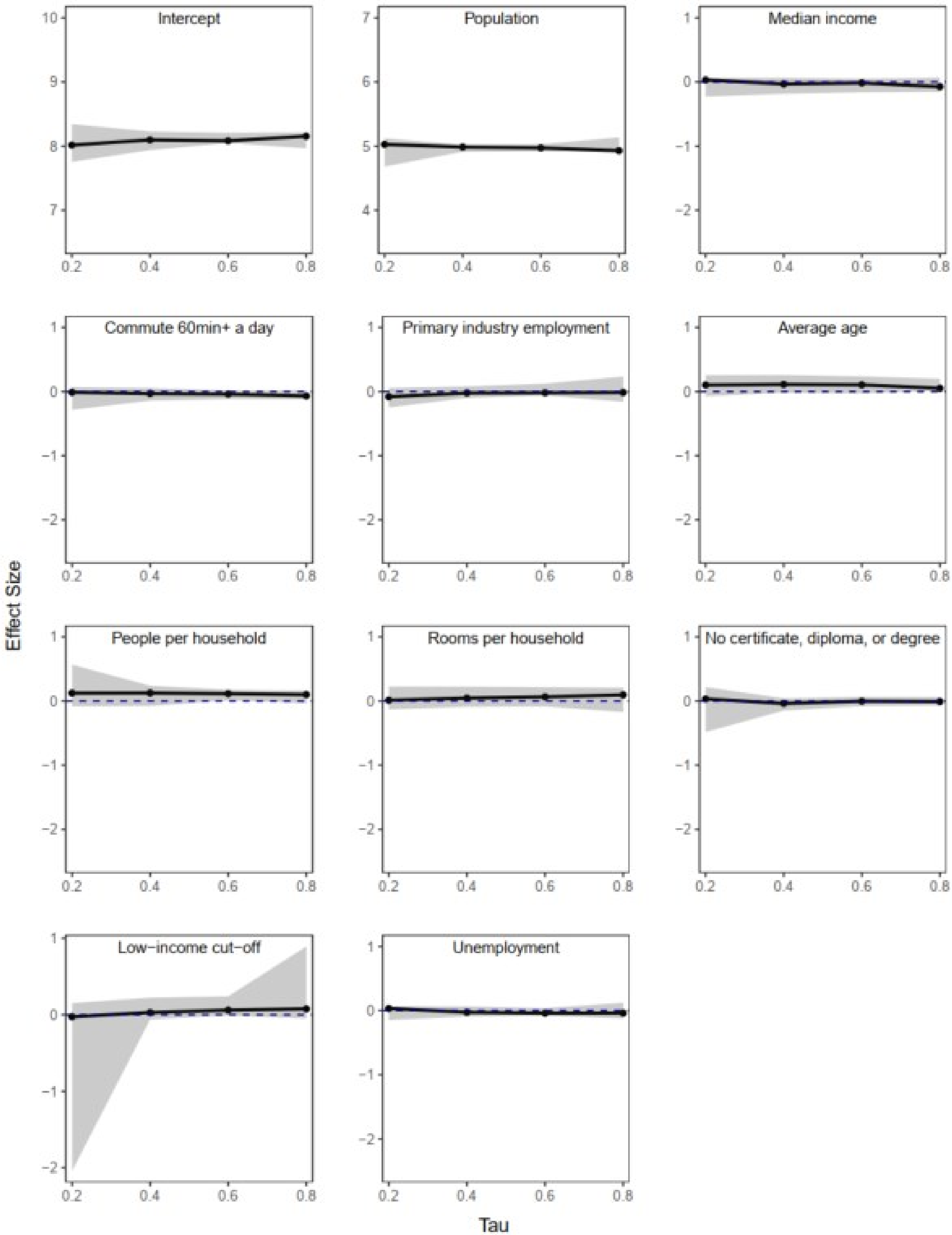

Intercept
Population
Median income
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.15| QR results for total community CO_2 emissions in Prince Edward Island where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

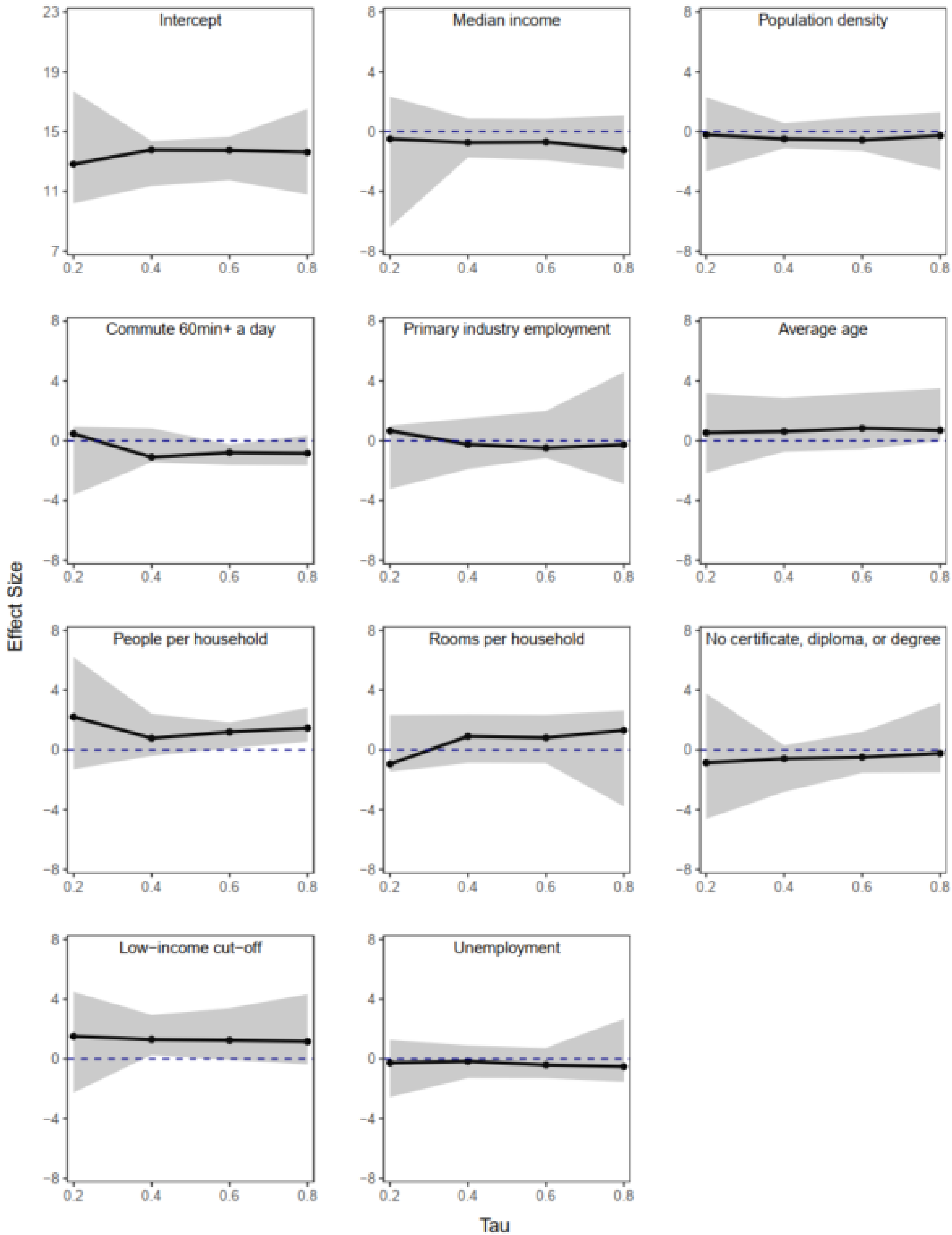

Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.16| QR results for per capita community CO_2 emissions in Prince Edward Island where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

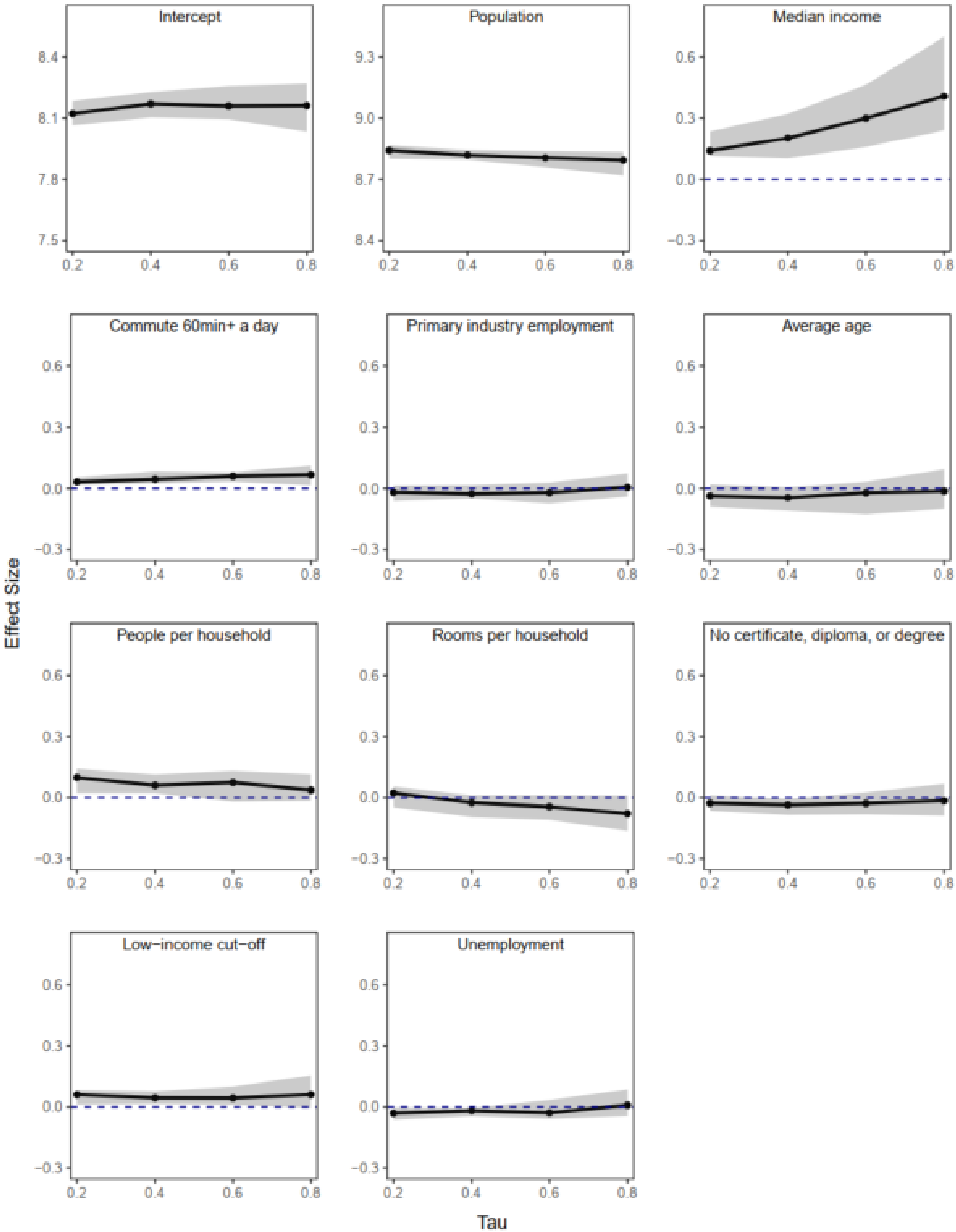

Intercept
Population
Median income
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.17| QR results for total community CO_2 emissions in Québec where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

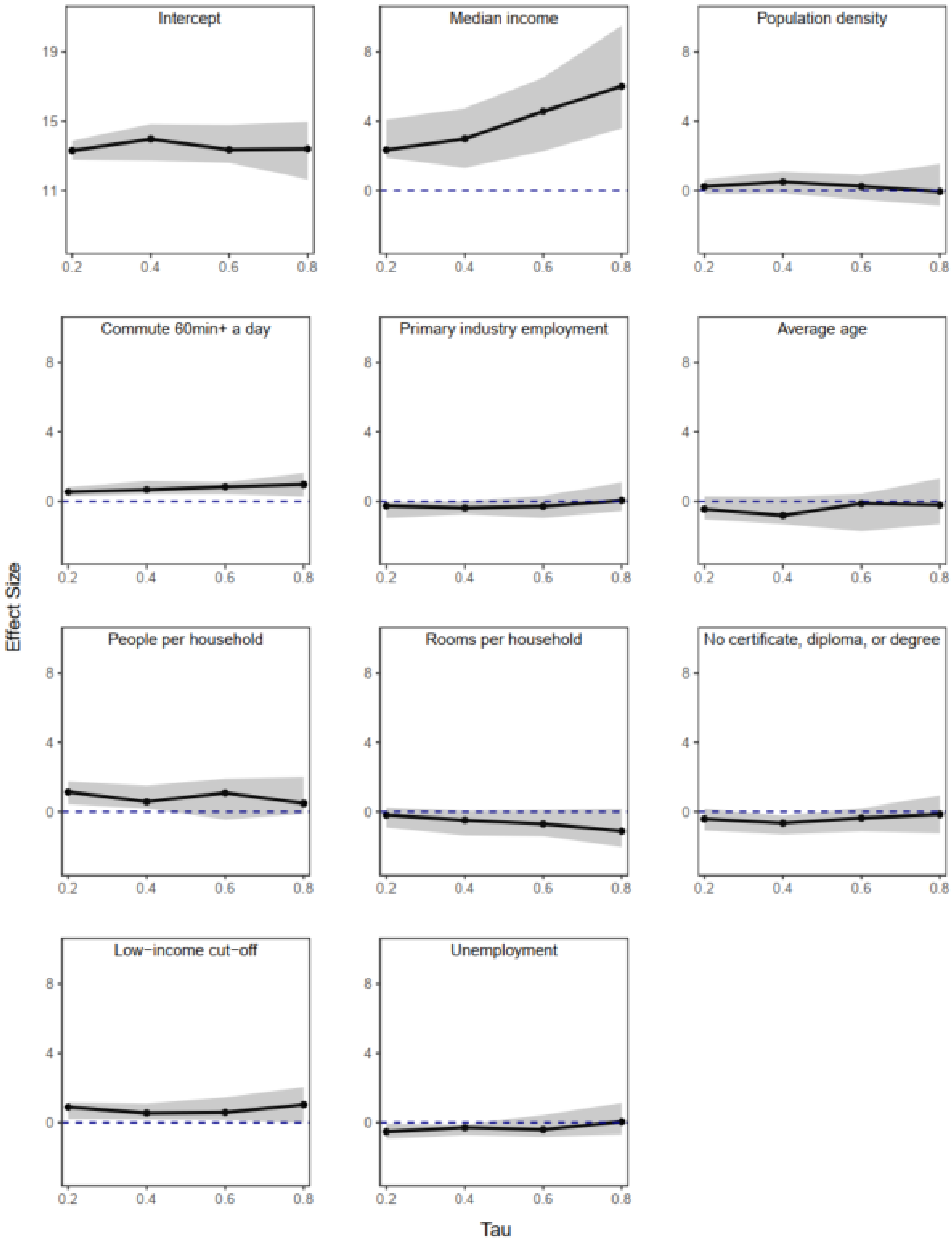
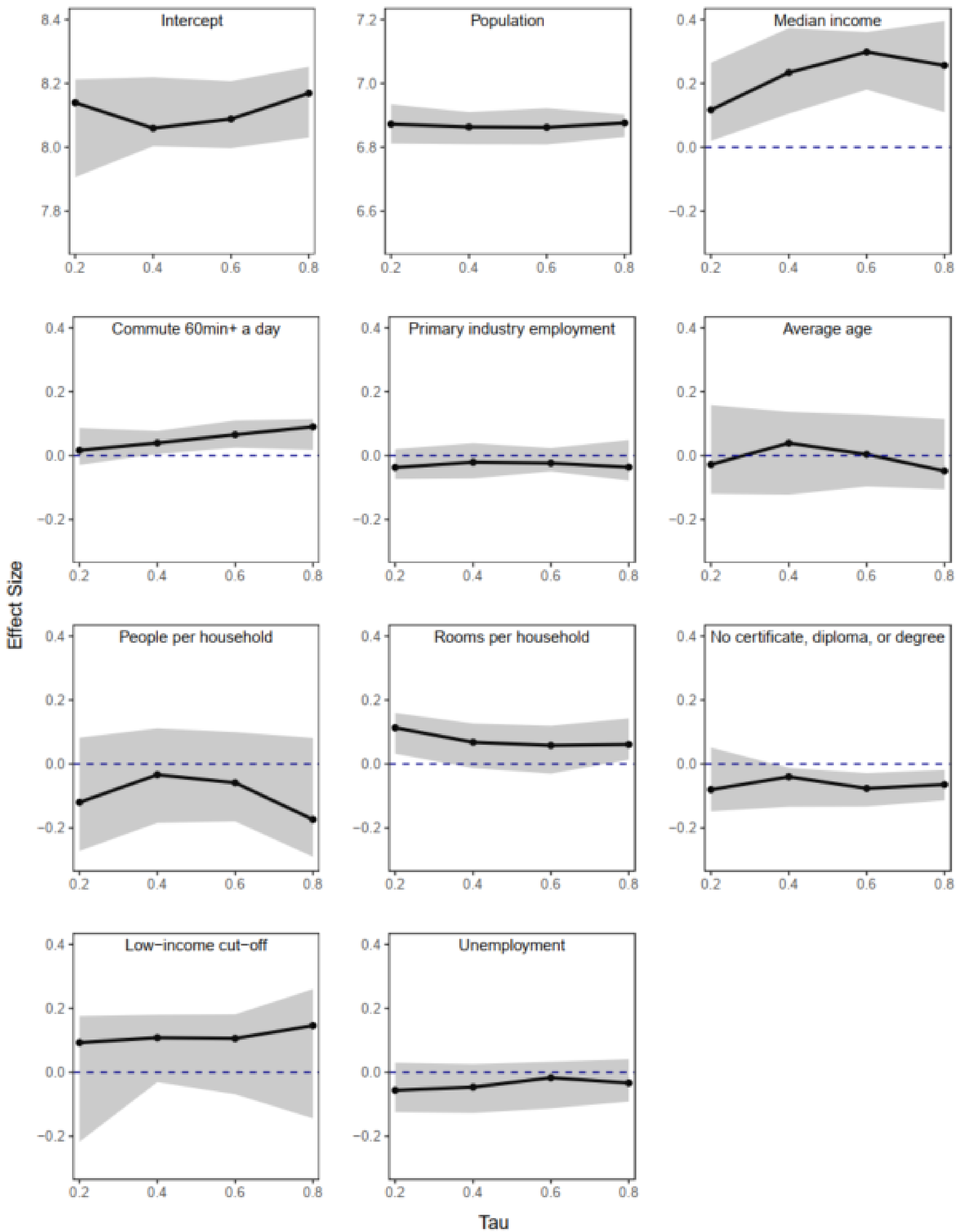

Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau
19
15
11
8
4
0
0.2
0.4
0.6
0.8

Figure A.18| QR results for per capita community CO_2 emissions in Québec where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.



Intercept
Population
Median income
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.19| QR results for total community CO_2 emissions in Saskatchewan where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.

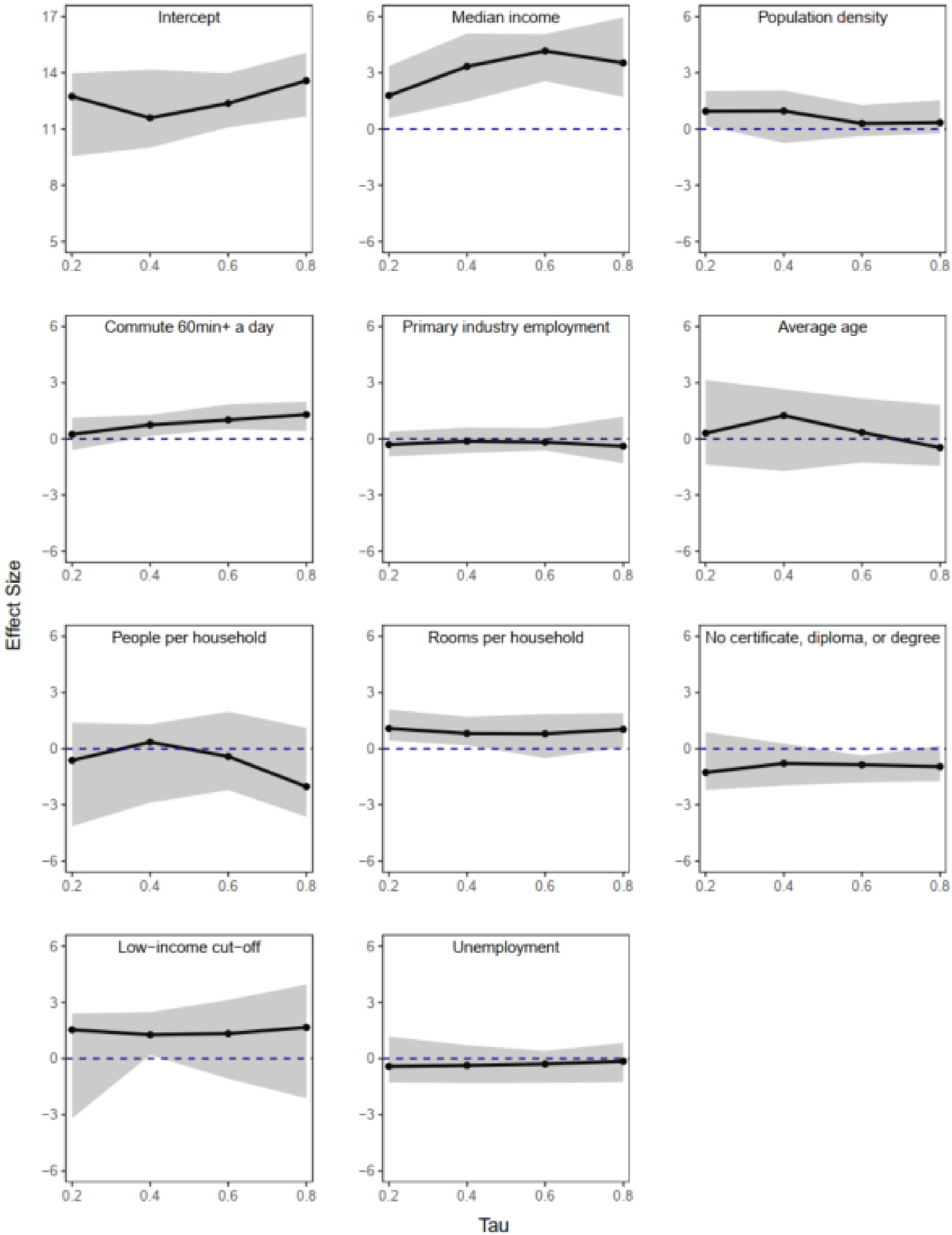

Intercept
Median income
Population density
Commute 60min+ a day
Primary industry employment
Average age
People per household
Rooms per household
No certificate, diploma, or degree
Low−income cut−off
Unemployment
Effect Size
Tau

Figure A.20| QR results for per capita community CO_2 emissions in Saskatchewan where the *y*-axis represents the effect size of each variable, and the *x*-axis represents the tau values used in the analysis. The shaded grey areas are the 95% confidence interval for each variable. If the 95% interval crosses over the zero horizontal dashed line, that variable is non-significant for that value of tau.