Identifying drivers of reactive nitrogen emissions and innovative nutrient policies using the Canadian geographic context

Sibeal McCourt

Department of Geography

McGill University

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Abstract

Excess reactive nitrogen (N_r) in the environment results in serious negative impacts to society including air pollution, eutrophication, and climate change. To better manage N_r there is a need to examine the underlying drivers of N_r emissions and to identify potential areas for intervention. However, gaps remain in our understanding of the drivers of N_r emissions because they are diverse and often complex. In this thesis, I address three specific gaps: accounting for sub-national geographic variation, understanding the effects of changes in economic structure on whole-economy N_r emissions, and integrating nutrient-related concerns comprehensively into policy. I undertake a series of analyses to inform these aspects of research into the drivers of N_r emissions and opportunities for policy integration in Canada. These three studies draw on multiple methodological and interdisciplinary approaches, including the development of a novel N footprint model, application of economic decomposition analysis methods, and a policy assessment that uses text and network analysis techniques. First, using my model of Canadian N footprints, I examine the patterns of provincial footprints and how consumption-oriented drivers of N_r emissions vary between provinces in relation to their diverse geographic contexts. I then expand on the footprint accounting perspective by exploring more detailed trends in N_r emissions across Canada over time. I do this by synthesizing data from a variety of sources to assess the role of socioeconomic drivers on whole-economy N_r emissions. My results from these two studies collectively show that provincial total and per capita N footprints and territorial emissions vary considerably based on population, affluence, and the relative economic importance of the fossil fuel and agriculture sectors across Canadian provinces. They also underscore the challenges of attributing N_r emissions for export-oriented economies like Canada's and emphasize the importance of improving emissions intensity and shifting economies toward less N_r intensive sectors. I then explore the nutrient-related policy

environment in Canada (i.e., federal and provincial legislative Acts with relevance to nitrogen and phosphorus) using semantic network analysis. My findings from this analysis reveal potential areas for policy integration in nutrient-related legislation in Canada. Finally, I reflect on the results of my three studies from different emissions accounting perspectives, examine how Canadian legislation matches (or does not match) previously identified drivers and sources of N_r emissions, and remark on the overarching geographic and provincial trends identified throughout this dissertation. Despite the difficulties in sustainably managing nutrients at the national scale given conflicting or competing economic, social, and environmental goals, my research demonstrates how the multifaceted nature of nutrient issues provides opportunities for innovative policies to address these challenges.

Résumé

L'excès d'azote réactif (A_r) dans l'environnement entraîne de graves impacts négatifs sur la société y compris la pollution de l'air, l'eutrophisation et le changement climatique. Pour mieux gérer le A_r, il est nécessaire d'examiner les facteurs sous-jacents des émissions de A_r et d'identifier les domaines potentiels d'intervention. Cependant, il existe des lacunes dans notre compréhension des moteurs des émissions de A_r car ils sont divers et souvent complexes. Dans cette thèse j'aborde trois de ces lacunes: le rôle des variations géographiques infranationales, les effets des changements de structure économique, et l'intégration des politiques de pollution par les nutriments. J'utilise le Canada comme étude de cas pour éclairer ces trois domaines de recherche. Mes études utilisent plusieurs méthodologiques interdisciplinaires, notamment le développement d'un nouveau modèle d'empreinte, l'application de méthodes d'analyse de décomposition économique, et une évaluation des politiques qui utilise des techniques d'analyse de texte et de réseau.

Tout d'abord, à l'aide de mon modèle d'empreintes canadiennes d’azote, j'examine les tendances des empreintes provinciales et la façon dont les facteurs d'émissions de A_r axés sur la consommation varient entre les provinces en fonction de leurs divers contextes géographiques. Je développe ensuite la perspective de comptabilisation de l'empreinte en explorant des tendances plus détaillées des émissions à travers le Canada au fil du temps. Je synthétise des données provenant de diverses sources pour évaluer le rôle des moteurs socio-économiques sur les émissions de A_r de l'ensemble de l'économie. Mes résultats de ces deux études montrent que les empreintes provinciales totales et par habitant, et les émissions territoriales varient considérablement en fonction de la population, de la richesse et de l'importance économique relative des secteurs des combustibles fossiles et de l'agriculture dans les provinces canadiennes.

Ils soulignent également les défis d'attribuer les émissions de A_r aux économies axées sur l'exportation, comme le Canada, et soulignent l'importance d'améliorer l'intensité des émissions et de déplacer les économies vers des secteurs moins intensifs en A_r. Ensuite, j'explore l'environnement politique lié aux éléments nutritifs au Canada (lois législatives fédérales et provinciales pertinentes à la fois pour l'azote et le phosphore) à l'aide d'une analyse de réseau sémantique. Mes conclusions révèlent des domaines potentiels d'intégration des politiques dans la législation relative aux nutriments au Canada. Enfin, je réfléchis aux résultats de mes trois études à partir de différentes perspectives de comptabilisation des émissions, j'examine comment la législation canadienne correspond (ou ne correspond pas) aux facteurs et sources d'émissions de A_r précédemment identifiés, et aux tendances géographiques et provinciales globales identifiées tout au long de cette thèse. Malgré les difficultés de gestion durable des nutriments à l'échelle nationale compte tenu des objectifs économiques, sociaux et environnementaux contradictoires ou concurrents, mes recherches démontrent comment la nature multiforme des problèmes de nutriments offre des opportunités pour des politiques innovantes pour relever ces défis.

Table of Contents

Abstract ii

Résumé iv

Table of Contents vi

List of Figures ix

List of Tables xi

Acknowledgements xii

Contribution of authors xiii

Chapter 1 Introduction 1

1.1 Research Context 1

1.2 Research Question/Objectives 4

1.3 Thesis Structure 5

Chapter 2 Literature Review 7

2.1 The nitrogen problem 7

2.2 Nitrogen accounting and indicators 9

2.3 Drivers of N_r emissions 11

2.3.1 Supply-chains and N footprints 12

2.3.2 Other socio-economic drivers 14

2.3.3 N_r policy integration and institutional drivers 16

2.4 The Canadian context 20

2.5 Literature Review Conclusions 23

Preface to Chapter 3 24

Chapter 3 Provincial nitrogen footprints highlight variability in drivers of reactive nitrogen emissions in Canada 26

3.1 Introduction 27

3.2 Methodology 31

3.2.1 Food production and VNFs 34

3.2.2 Food origin scenarios 38

3.2.3 Food consumption 38

3.2.4 Wastewater treatment 39

3.2.5 Fossil Fuels 40

3.3 Results and Discussion 41
3.3.1 Food production and consumption.. 43
3.3.2 Fossil fuels 49
3.3.3 Attributing top-down N footprint emissions from fossil fuels 50
3.3.4 N_r reduction policies and future research.. 52
3.4 Conclusions.. 52
3.5 References.. 54
Preface to Chapter 4.. 61
Chapter 4 Decomposing three decades of nitrogen emissions in Canada 62
4.1 Introduction.. 64
4.2 Materials and Methods.. 67
4.2.1 An inventory of N_r emissions between 1990 and 2017 67
4.2.2 Classification of N_r emissions into source sectors 69
4.2.3 Decomposition analysis 70
4.3 Results and discussion 72
4.3.1 Trends in total and per capita N_r emissions 72
4.3.2 The role of regulatory policy in decreasing fossil fuel N_r emissions.......................... 75
4.3.3 Shifting agricultural N_r emissions and policy gaps.. 79
4.3.4 Technology and efficiency improvements can offset positive drivers of growth in total N_r emissions 81
4.3.5 Sectoral N_r emissions and the influence of economic structural changes 83
4.3.6 Uncertainties and limitations 85
4.4 Conclusions.. 87
4.5 References.. 89
Preface to Chapter 5.. 93
Chapter 5 Identifying leverage points for sustainable nutrient policy integration in Canada 94
5.1 Introduction.. 95
5.2 Results and Discussion 97
5.2.1 Nutrient legislation topic classification. 98
5.2.2 Cross-cutting ‘hub’ and ‘bridge’ legislation 100
5.2.3 Similarities and differences in N and P networks 103

5.2.4 Role of indirect legislation in novel nutrient policy integration 105
5.2.5 Alternative network classifications and uncertainties............ 106
5.3 Toward greater nutrient policy integration 107
5.4 Methodology: 109
5.4.1 Identifying Nutrient-Related Legislation 109
5.4.2 Semantic Network Analysis............ 110
5.5 References............ 113
Chapter 6 Discussion 116
6.1 Comparing Prairie and central provinces: production vs consumption 116
6.2 Producer-consumer responsibility: accounting for exports 122
Chapter 7 Conclusions and future research 126
7.1 Original contributions to research............ 126
7.2 Directions for future research 128
7.4 Closing remarks 130
References for non-manuscript chapters............ 131
Supplementary Materials 152

List of Figures

Figure 1.1 Thesis Outline including the relationship among the three manuscript (analysis) chapters. 6

Figure 2.1 The major components of food system NUE in a national food system 11

Figure 2.2 An example of Canadian geographic heterogeneity shown by the terrestrial ecozones across the 10 Canadian provinces 20

Figure 3.1 Overview of the 10 Canadian provinces in terms of population, agricultural and energy characteristics that affect N footprints. 30

Figure 3.2 Diagram illustrating the key components of our top-down N footprint model. 32

Figure 3.3 Total provincial N footprints by sector (A), per capita provincial N footprints by sector (B), and the relative contribution of each sector to a provinces' per capita footprint (C). 42

Figure 3.4 Per capita provincial N footprints by subsector (A), and the contribution of each subsector to each provinces' per capita footprint (B). 43

Figure 3.5 Provincial virtual nitrogen factors (VNFs, g N kg food^{-1}) for different food groups.. 45

Figure 3.6 Sensitivity analysis using different VNFs to estimate national and provincial virtual nitrogen footprints (N kg cap^{-1} year $^{-1}$) from consumption of crops and animal products. 47

Figure 3.7 Wastewater sensitivity analysis examining different assumptions about recycling versus landfilling biosolids and sludge from wastewater treatment (N kg cap^{-1} year 1). 48

Figure 4.1 Breakdown of total (Gg N year^{-1}) and per capita (kg N capita^{-1} year^{-1}) N_r emissions, nationally (a and b, respectively) and by province (c and d, respectively), between 1990 and 2017 73

Figure 4.2 Summary and comparison of Nr species from agricultural sources (left side) with those from fossil fuel combustion (right side) nationally (a, b) and for each province (c, d) from 1990 to 2017. 76

Figure 4.3 Classification of relative subsector and N_r species contributions as a percentage of total N_r emissions in each province and nationally between 1990 and 2017............................... 78

Figure 4.4 Changes in provincial N_r emissions compared to changes in (a) GDP (in billion $CAD, current dollars), (b) population, and (c) GDP per capita (thousand $CAD) between 1990-2017.. 82

Figure 5.1 The network of nutrient-related Acts across Canada. 99

Figure 5.2 Phosphorus (left side, a and c) and nitrogen (right side, b and d) related policies across Canada depicted as network graphs. 104

Figure 5.3 Flow chart depicting process of Act selection and screening for the semantic network analysis in this study. 110

Figure 6.1 A comparison of different accounting perspectives. 117

List of Tables

Table 3-1: Overview of N flow methodologies and data sources for the N footprint model in this study 33

Table 3-2 Per capita fossil fuel emissions from three methodologies, nationally and for two major oil and gas dependent provinces, Alberta, and Saskatchewan. 51

Table 4-1 Categories of N_r species included in the emission synthesis by source sector and subsector. 69

Table 4-2 Decomposition of changes in overall N_r emissions between 1990 and 2017 across Canada and the provinces of Alberta, Saskatchewan, and Ontario. 82

Table 4-3 Decomposition of sectoral changes in N_r emissions from two NAICS economic sectors, agriculture and oil & gas, between 1990 and 2017 across Canada and the provinces of Alberta, Saskatchewan, and Ontario. 84

Table 5-1. List of topics identified by a Leiden clustering analysis of Canadian nutrient-related legislation (using a clustering resolution of 1.35). 100

Table 5-2 Top five hub and bridge acts in the Canadian nutrient network as measured by their closeness and Burt's constraint scores respectively 101

Table 6-1 Comparison of total and per capita Nr emissions using an N footprint approach compared to a synthesis of national and provincial emissions inventories. 119

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Contribution of authors

This thesis includes three manuscripts that are either published at or submitted to a journal. These manuscripts were written with co-authors, whose contributions are as follows.

Manuscript 1 (Chapter 3): "*Provincial nitrogen footprints highlight variability in drivers of reactive nitrogen emissions in Canada*" by Sibeal McCourt and Graham MacDonald. Sibeal McCourt led the conceptualization, N footprint model development, data collection, data analysis, and writing. Graham MacDonald contributed feedback throughout the conceptualization and analysis stages and reviewed and commented on the manuscript. Chapter 3 is published in *Environmental Research Letters* can be found at:

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Manuscript 2 (Chapter 4): "*Decomposing three decades of nitrogen emissions in Canada"* by Sibeal McCourt and Graham MacDonald. Sibeal McCourt led the conceptualization, data collection, data analysis, and writing. Graham MacDonald contributed feedback throughout the conceptualization and analysis stages and provided detailed feedback on the manuscript. Chapter 4 is published in *Future Earth* and can be found at:

> McCourt, S., & MacDonald, G. K. (2022). Decomposing three decades of nitrogen emissions in Canada. *Earth's Future*, e2022EF002774.

Manuscript 3 (Chapter 5): "*Identifying leverage points for sustainable nutrient policy integration in Canada*" by Sibeal McCourt, David Kanter, and Graham MacDonald. Sibeal McCourt led the conceptualization, data collection, analysis, and writing. David Kanter and Graham MacDonald contributed feedback throughout the conceptualization and analysis stages and provided feedback on the manuscript. Chapter 5 will be submitted to a journal in 2023. It has been formatted according to requirements for the journal *Nature Sustainability*.

Chapter 1 Introduction

1.1 Research Context

Excess reactive nitrogen (N_r, commonly defined[1] as any form of nitrogen other than the gaseous N_2 that makes up most of our atmosphere; Galloway et al., 2002) in the environment is resulting in serious negative consequences, including climate change, impacts to human health, biodiversity, and environmental quality (Galloway et al., 2003; Lade et al., 2020). The global N biogeochemical cycle has been massively disrupted. The planetary boundary for nitrogen, the amount of new N_r that can be 'safely' added to the environment without creating major disturbance, is estimated to be 57 Tg yr^{-1}. Anthropogenic sources currently contribute a surplus of 119 Tg N yr^{-1}, far above this proposed limit (Schulte-Uebbing et al., 2022). Reducing excess N_r is complex problem for several reasons (Morseletto, 2019). Not only is N_r released from multiple sources (e.g., inefficient fertilizer use, fossil fuel combustion, wastewater), some of which are non-point source and difficult to regulate, it is also highly mobile in the environment (Galloway et al., 2003). Additionally, there is the competing goal of needing to increase the amount of N_r available in our food system in order to feed the global population as it continues to grow both in numbers and in wealth (Bodirsky et al., 2014; Springmann et al., 2018; Tilman et al., 2011).

To balance future increases in N_r demands, while mitigating negative effects of N_r, there is a need to quantify the pressures and drivers of N_r emissions to identify potential areas for intervention (Houlton et al., 2019b; Kanter, Del Grosso, et al., 2020; Malik et al., 2022). At the

[1] For the purposes of this thesis, which focuses on human dimensions of the nitrogen cycle, my use of N_r generally encompasses NH_3, NO_x, NO^-_3, NO^-_2, and N_2O unless otherwise specified.

global scale, previous studies have identified population growth, affluence, meat consumption, and international food trade as important drivers of N_r emissions (e.g., Lassaletta, et al., 2014; Malik et al., 2022; Oita et al., 2016; Wang et al., 2022). However, there are important gaps in our knowledge of drivers of N_r emissions. Many studies on the drivers of N_r emissions are consumption-oriented 'footprint' approaches (indicators that quantify consumers' pressure on the environment through resource use and emissions) (Vanham et al., 2019), and most are at the national level and report their findings as a national per capita average. Furthermore, the footprints often aggregate multiple N_r species to total N (e.g., Dhar et al., 2022; Leach et al., 2012; Oita et al., 2016; Shibata et al., 2014). This may obscure important details in drivers of N footprints, especially in large countries, and therefore potential strategies to reduce N_r pollution. Additionally, we have a limited understanding of the impact of a range of other socio-economic factors on N_r emissions (Malik et al., 2022). Finally, effective N_r management needs policy integration, including with other nutrients, such as phosphorus. Where it exists, nutrient policy is characterized by limited co-ordination and partial coverage of sources and impacts. A better understanding of the nutrient policy landscape could enable more effective policy through better policy integration (Kanter, Chodos, et al., 2020; Morseletto, 2019; A. L. Yang et al., 2022).

My thesis addresses the research gaps identified above, using Canada as a case study. Canada provides an illustrative example to undertake assessments of drivers of N_r emissions and nutrient policy. There has been relatively limited research into the drivers of N_r emissions in Canada—a large socioeconomically and geographically diverse country. In this thesis I therefore use Canada to inform new aspects of research into drivers of N_r emissions, drawing on an interdisciplinary approach that includes model development, synthesis of trends over varying spatial and temporal scales, multiple accounting perspectives, as well as policy analysis. My findings provide insight into substantial spatio-temporal variation in drivers and policy in Canada, which could also be informative to studies on N_r emissions and nutrient policy in other regions.

1.2 Research Question/Objectives

This dissertation responds to gaps in understanding drivers of Nr emissions outlined above. The guiding research questions for this thesis are:

(1) How do consumption-oriented N_r drivers vary with different regional geographic contexts across a large country?

(2) What is the role of changing economic structure in whole-economy N_r emissions?

(3) What opportunities do nutrient-related legislation provide to support innovative nutrient policy integration?

Accordingly, my specific research objectives pertaining to my focus on Canada are to:

(a) Develop a nitrogen footprint model for Canada that reflects subnational variation in production and consumption contexts between provinces;

(a) Examine the change in drivers of N_r emissions in Canada over time through decomposition analysis, reflecting the important socio-economic differences between provinces; and,

(a) Examine the nutrient legislation environment in Canada using a semantic network analysis to identify potential for novel nutrient policy integration.

1.3 Thesis Structure

This thesis comprises seven chapters, including this introductory chapter. Figure 1.1 shows the outline of my dissertation, how the chapters confront the three overarching gaps in N_r accounting research outlined above, and how the chapters relate to each other. Chapter 2 is a literature review on nitrogen emission research and the methodological approaches I draw on, beginning with on overview of several N_r accounting studies, then examining research into socio-economic drivers of N_r emissions and supply chain accounting perspectives followed by a summary of policy integration concepts and major N_r policy developments. I conclude chapter 2 with a summary of nitrogen related research in Canada. The main body of this thesis is comprised of my three manuscript chapters, which have been published in, or will be submitted to, peer-reviewed journals. The first manuscript, Chapter 3, presents the development of a new N footprint model for Canada, and examines how results vary between provinces in relation to their diverse geographic and socio-economic contexts. Chapter 4 examines trends in N_r emissions across Canada over time, synthesizing data from a variety of sources. In chapter 4, I also perform, what is to my knowledge, the first whole-economy index decomposition analysis of N_r emissions. The final manuscript, Chapter 5, applies semantic network analysis to examine the nutrient regulation environment in Canada, applying a novel methodology to identify potential for nutrient policy integration. The discussion section of the dissertation, Chapter 6, synthesizes my findings from the three analyses presented in the manuscript chapters. I summarize the overarching geographic and provincial N_r trends identified throughout this dissertation then compare and contrast the drivers identified by using different accounting methods described in Chapters 1 and 2. Finally, my conclusions (presented in Chapter 7) summarizes the main results of this dissertation and discusses potential implications for future research.

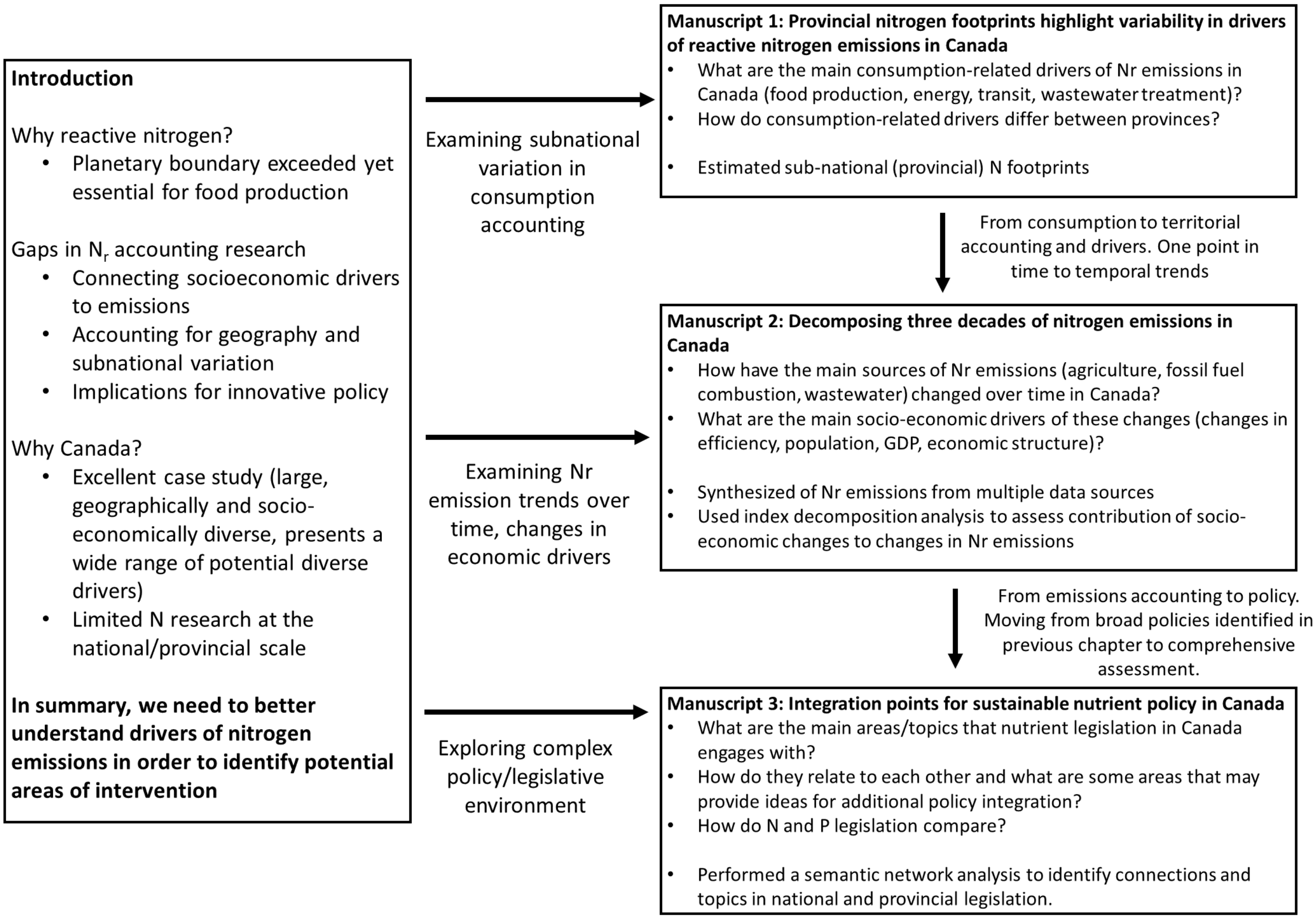

Figure 1.1 Thesis Outline including the relationship among the three manuscript (analysis) chapters.

Chapter 2 Literature Review

In this chapter, I summarize the existing literature relevant to this thesis. I begin with an overview of our understanding of the global nitrogen problem, the negative impacts of excess N in the environment, and the scale of the issue. I review major concepts such as nitrogen use efficiency (NUE) and summarize large-scale N budget assessments to highlight areas that have been recognized as crucial sources and flows of N_r. With this starting point, I then discuss different methodological and conceptual N accounting approaches that can be used to identify underlying drivers of these N_r emissions. Given that the term "driver" is broad and used in diverse contexts in literature on N_r emissions (Malik et al., 2022), for this literature review I organize the discussion on drivers into 3 broad categories: *supply-chain drivers* (consumer vs producer), *socio-economic factors* (population, affluence, diet, etc.), and *structural influences* (policies, educational programs, financial incentives, etc.). Finally, I discuss the Canadian context as it pertains to each section and demonstrate why Canada is an excellent case study to examine the knowledge gaps I have identified.

2.1 The nitrogen problem

Nitrogen is one of the major building blocks of life. It is a key component of nucleic acids and proteins in every living creature. Yet, even though nitrogen gas (N_2) is almost 80% of the Earth's atmosphere, this reservoir of N is not biologically available to most organisms (Galloway, 2014). Breaking the stable N_2 molecule so that N that can be incorporated into proteins is an energy intensive process, and in nature this is mostly accomplished by a few specialized organisms including blue-green algae and some symbiotic bacteria on the roots of leguminous plants (e.g. soybeans and clover) (Galloway & Cowling, 2002, 2021).

In the early 1900's, the Haber-Bosch process was developed to produce ammonia (NH_3) by reacting atmospheric N_2 with hydrogen at high temperature and pressure using iron as a catalyst. NH_3 is a biologically available form of reactive nitrogen (N_r), any kind of nitrogen other than N_2, and so the Haber-Bosch process allowed for the creation of synthetic fertilizers at an industrial scale. This in turn dramatically increased agricultural productivity across most of the world, and synthetic fertilizers were estimated to produce the additional calories needed to feed ~40% of the world's population by the 2000s (Erisman et al., 2008).

Through increased synthetic fertilizer use, expanding cultivation of N-fixing crops, and burning fossil fuels (N_r is released to the atmosphere both through oxidizing atmospheric N_2 during combustion and by releasing N contained in fossil fuels), each year more and more N_r is being created through anthropogenic sources. In the 1990's, it was estimated that ~140 Tg N_r was created by human activities (Vitousek et al., 1997). In 2010, N_r created through anthropogenic activities was estimated to be ~210 Tg N_r (Fowler et al., 2013), and by 2020, the estimate had risen to ~240 Tg (Galloway & Cowling, 2021)—nearly doubling the amount of N_r created through natural ecosystems.

While increased N_r has been beneficial for improving agricultural productivity, excess N_r is now accumulating in the environment, and can have multiple negative consequences to the environment and human health. NH_3 and nitrous oxides (NO_x) emissions to the atmosphere can cause induce serious respiratory illness, cancer, and cardiac disease in humans, and when mixed with water can cause acidification and loss of biodiversity. Ammonia and nitrate (NO_3^-) in water can lead to eutrophication, groundwater contamination, hypoxia, and habitat degradation and is a significant issue in many coastal areas. Nitrous oxide (N_2O) is a greenhouse gas and contributes to ozone depletion. With seven oxidative states, numerous environmental pathways for transport and conversion between species, a single molecule of N_r can create multiple impacts in sequence as it moves through the environment, a process referred to as the 'nitrogen cascade' (Galloway et al., 2003, 2004)

The magnitude of the addition of N_r to the environment has resulted in grave concern as to the state of the global N biogeochemical cycle. It has been posited that the planetary boundary for nitrogen (the amount of N_r which can safely be added to the environment in a 'safe operating space before Earth systems may fundamentally change and put humanity is at risk) has been exceeded, although due to the complex nature of the N biogeochemical cycle and other earth system processes it is still under debate as to by how much (de Vries et al., 2013; Lade et al., 2020; Steffen et al., 2015).

2.2 Nitrogen accounting and indicators

There is increasing scientific and political interest in managing the nitrogen problem. Controlling and reducing emissions requires that they be measured and accounted for. Tracking anthropogenic nitrogen through the environment is a challenge, however estimating N budgets, (quantifying stores and flows of N), is a critical first step to identifying where N_r losses to the environment could be reduced and to track progress towards different environmental goals (Galloway et al., 2004; Sutton et al., 2021).

There have been several global assessments (e.g. Fowler et al., 2013; Galloway et al., 2004), as well as an increasing number of national N budgets (e.g. for the United States (Sabo et al., 2019), Germany (Häußermann et al., 2021), Denmark (Hutchings et al., 2014), China (Cui et al., 2013) and Japan (Hayashi et al., 2021)) published in the last decade. Creation of NH_3 for fertilizer application and cultivation-induced biological N fixation (CBNF) are the main sources of new N_r

globally and are increasing across most of the world. But, depending on the study area, fossil fuel combustion for transport and energy generation are also important sources of N_r emissions to the environment, although this source of N_r is decreasing in many areas (Galloway et al., 2021). Agricultural N budgets at the national level (e.g. the United States (J. Zhang et al., 2021), France (Le Noë et al., 2017)) and global level (Lassaletta et al., 2016; X. Zhang, 2021) show large losses of N_r through leaching and volatilization.

A complementary indicator to estimating N budgets is nitrogen use efficiency (NUE). NUE indicates whether N_r is being used effectively: enhancing agricultural productivity and minimizing losses of N_r to the environment. NUE can be defined and quantified in several ways, and with different purposes across scales (from crop field to country). One of the more common definitions is to use crop production and the ratio of N taken up in crop yields over the amount of total N inputs applied to soils (Lassaletta, Billen, Grizzetti, Anglade, et al., 2014). It is currently estimated that the global NUE of crop production is less than 50% (X. Zhang et al., 2015). However, we can also assess the NUE of crop and livestock systems (Hutchings et al., 2020), whole food systems (Erisman et al., 2018) or entire economies (Sutton et al., 2013). When assessing NUE across the whole food system we include the entire chain of producers, collectors, processors, distributors, retailers, and consumers (see Figure 2.1). Therefore NUE for the whole food system is the ratio of N_r available for food consumption to the new N_r used to produce that food (Erisman et al., 2018). NUE for an entire economy adds N_r creation from energy use and transport, so whole-economy NUE is the amount of N_r consumed over all anthropogenic N_r

emissions. Globally, whole-economy NUE is currently estimated to be at ~8% (Sutton et al., 2013).

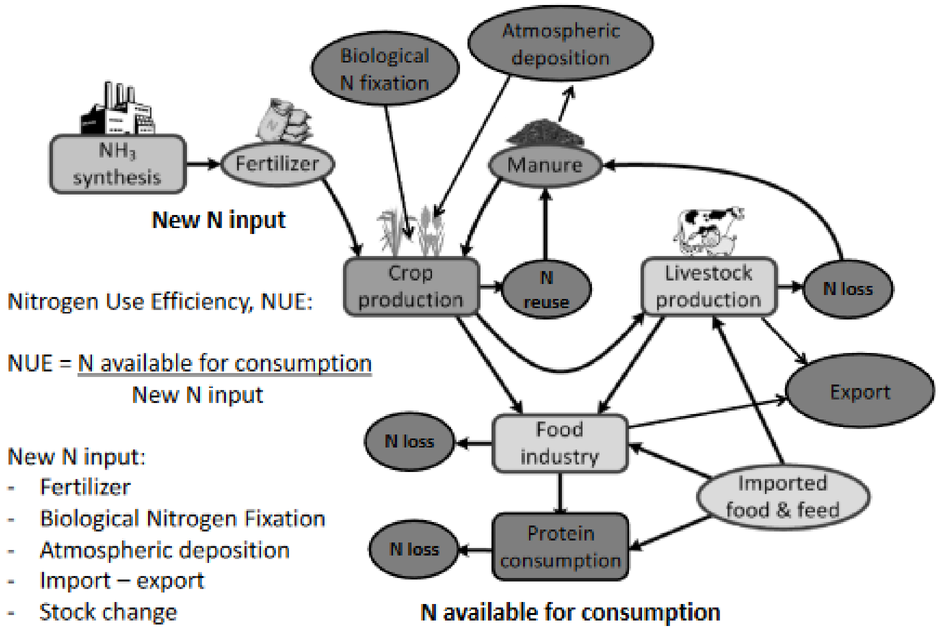

Figure 2.1 The major components of food system NUE in a national food system Figure from Erisman et al. (2018).

2.3 Drivers of N_r emissions

While there has been some success in reducing fossil fuel-related N_r emissions through legislation and a general trend towards more renewable source of energy in some regions, there has often been less success in regards to agricultural N_r emissions. Competing goals to produce more food but protect the environment, and the multitude of actors influencing N_r losses along an increasingly globalized food supply chain, make decreasing agricultural N loss a ‘wicked problem’ (Galloway & Cowling, 2021; Kanter et al., 2019). There is increasing interest in quantifying underlying drivers of N_r emissions in order to identify new pressure points to reduce emissions (Malik et al., 2022). The following sections discuss supply-chain drivers, socio-economic factors, and structural influences as they relate to N emissions, and highlight some gaps in the literature where additional research is needed.

2.3.1 Supply-chains and N footprints

N budgets and NUE indicators, while useful in identifying major flows of N_r inputs and outputs do not explicitly focus on how mitigation responsibility could be assigned. Accounting for emissions is the first step towards allocating reduction responsibility. Accordingly, three major principles for allocating reduction responsibility along a supply-chain have been described in the literature: producer, consumer and shared responsibility (Lenzen & Murray, 2010).

In the past ten years there has been a surge of interest in examining the role of consumers as an alternative to solely focusing on producers as drivers of N emissions. Consumption-oriented accounting, or 'N footprints' account for all upstream losses of N_r due to the consumption of a good or service. Footprint analysis has parallels to Life Cycle Assessment (LCA) and both are based on 'life cycle' thinking, however, they differ in their aim and system boundaries. Footprints are concerned with environmental 'pressures' (resource use or emissions) whereas LCA is impact oriented (Einarsson & Cederberg, 2019; Vanham et al., 2019).The footprint concept has been widely used since the term was originally coined (as the Ecological Footprint) in 1996 by Rees & Wackernagel. Footprints have been used in relation to carbon, water, and land usage (Vanham et al., 2019). The popularity of footprints as an accounting tool is due, in part, to the fact that footprints can give policymakers and scientists a goal to work towards. For example, footprints converge well with the concept of planetary boundaries. (e.g. with the planetary boundary for N of 62 Tg yr^{-1} that translates to a N footprint goal of ~8 kg $person^{-1}$ $year^{-1}$ (Vanham et al., 2019)).

The first N-specific footprint model (the N-Print model) was developed by Leach et al. (2012). The N-print model uses estimates of Virtual Nitrogen Factors (VNFs) to calculate N footprints. "Virtual" nitrogen is the amount of nitrogen that is released to environment during the production and consumption of a good, for every unit of the good. Alternatively, VNF is sometimes defined as the ratio of nitrogen released during production and consumption of a good compared to the N_r contained in the item itself (Galloway et al., 2007). The N-print model uses a hybrid top-down and bottom-up approach to estimate an entity's N-footprint, combining data on individual food and energy consumption with national statistics on total energy production.

N footprints have been estimated for several countries. The N-Print model has been used to estimate the average N footprint for the United States and the Netherlands (Leach et al., 2012), Japan (Shibata et al., 2014), the United Kingdom (Stevens et al., 2014), Austria (Pierer, Winiwarter, Leach, & Galloway, 2014), Australia (Liang et al., 2016), Tanzania (Hutton et al., 2017), Egypt (Elrys et al., 2019), and Thailand (Mungcharoen & Suwanmanee, 2021). Other methods have been used to estimate N footprints for China (Gu et al., 2013) and Japan (Shindo & Yanagawa, 2017), and a multi-regional input-output model (MRIO) was used in global study of all nations (Oita et al., 2016). Partial food-system N footprints have been estimated for the European Union (Leip et al., 2014), China, India, Japan (Dhar et al., 2022; Oita et al., 2020; Shindo et al., 2020), Germany (Klement et al., 2021), Rwanada (Harerimana et al., 2021), and Sweden (Einarsson et al., 2022). There have also been adapted N-print studies performed at smaller scales, such as the city (Dukes et al., 2020; Xian et al., 2022) or institution (MacDonald et al., 2020; Martinez et al., 2019). Most of these studies identify meat consumption, in particular beef, and consumption of energy created through coal burning as important drivers of N_r emissions.

National-level N footprint studies typically report their findings as national totals and per capita averages (e.g., kg N $capita^{-1}$). This may mask important subnational differences in per capita footprints, especially in large countries with substantial spatial variability in socio-environmental conditions, such as Canada (Godar et al., 2015). Detailed VNFs are also currently unavailable for many countries, and many of the above-mentioned studies have used VNFs developed by Leach et al. (2012) for the U.S. as proxies. Estimating additional national and sub-national VNFs will therefore enable improved accounting of international N footprints.

2.3.2 Other socio-economic drivers

Other than N footprints, there has been relatively limited research into socio-economic drivers behind N_r emissions (Malik et al., 2022). There are a wide range of other important socio-economic drivers of N_r emissions that are not elucidated upon by N footprints including, for example, improvements in technology, or changes in economic structure. One method frequently used to measure the association between changes in socio-economic indicators and environmental measurements is decomposition analysis. First used in the 1970's as a way to study the impact of changes in production on industrial energy demand, decomposition analysis began as straightforward formulae that computed a hypothetical aggregate energy intensity (energy consumption over production) for a target year if sectoral energy intensities for all industries remained unchanged from a base year (Ang & Zhang, 2000). The difference between the hypothetical energy intensity in the target year and the observed energy intensity in the base year can be defined as the impact of structural change. The difference between the hypothetical and observed energy intensity in the target year can be defined as the impact associated with changes in sectoral energy intensity (Ang & Zhang, 2000).

Several more mathematically complex decomposition methods have been proposed over the years, and can be broadly broken down into either structural decomposition analyses (SDA, which use input–output models and data as a basis for decomposition) or index decomposition analyses (IDA, which use aggregate sector information) (de Boer & Rodrigues, 2020; Hoekstra, 2003). Both types of decomposition analysis are widely used as a research tool to study drivers of change in an array of research areas, and are popular in energy and environmental analysis (Ang, 2004; Ang & Zhang, 2000).

Several country-level assessments have been undertaken using decomposition analysis to examine pressures behind changes in N_r emissions over time, however they often focus on only one species of N_r or only one economic sector. For example, an IDA study of the EU found that growth in GDP per capita increased NO_x and NH_3 emissions up to a certain point and then decoupled (following the Environmental Kuznets Curve hypothesis), and increasing energy consumption increased NO_x and NH_3 emissions (Hnatyshyn, 2018). Another study using IDA to examine non-CO_2 greenhouse gas emissions from agriculture in India showed that there were large increases in N_2O emissions over the study period, which positively correlated with growth in fertilizer intensity (fertilizer use per unit of land), affluence and population. On the other hand the study found that relative contribution of agriculture to national GDP, and improved agricultural output per unit of fertilizer use or unit of cultivated land kept emissions lower than they otherwise might have been (Some et al., 2019).

However, due to the complexity and mobility of N_r in the environment, for N_r management to be effective it is often beneficial to take a "Total N_r Approach" which accounts for all species of N_r (Galloway & Cowling, 2002). I am aware of only two published studies that use decomposition analysis to examine changes in total N_r emissions of an economy. One of the studies examined drivers of national-scale N_r emissions in Denmark using SDA and identified rising exports and technological change as key factors driving national N_r emissions (Wier & Hasler, 1999). The second was a global scale analysis, which also used SDA, and found that combined pressure from increasing affluence, population growth, and changes in final demand outpaced any emission reductions driven by improvements in NUE (Malik et al., 2022). Comprehensive new whole-economy N_r decomposition studies can provide additional insight into drivers of overall N_r emissions.

2.3.3 N_r policy integration and institutional drivers

Understanding supply chain and socioeconomic drivers of N_r emissions is important in encouraging more efficient N_r use. But scientists and policy makers must also take into account the institutional and structural environment that influences actors (educational programs, financial incentives, and regulations, etc.). New and innovative measures are needed to address N_r pollution, and nutrient pollution in general.

There are benefits to addressing the management of phosphorus and nitrogen together. Both nutrients derive overwhelmingly from agricultural sources. This means that measures to reduce pollution of one nutrient can reduce the other. Additionally, one of the main environmental impacts of N_r, eutrophication, is a function of the interaction between nitrogen and phosphorus pollution, so in some cases an individual approach focused on a single nutrient may not resolve the underlying problem (Houlton et al., 2019a; Kanter & Brownlie, 2019; Metson et al., 2020).

Despite its social and environmental relevance, nutrient pollution still lacks coordinated global (and sometimes regional) governance (Garske & Ekardt, 2021; Sutton et al., 2021). This reflects the existing policy landscape, in which strategies often address disparate sources (industry, transport, agriculture, waste, etc.). But nutrient management is also considered a 'wicked problem', especially in regards to agriculture, a sector with multiple diverse actors, and where there are conflicting goals to protect the environment while producing more food (DeFries & Nagendra, 2017; Galloway et al., 2021).

Traditionally, agricultural nutrient reduction policies have focused on farm management, with mixed results (Lintern et al., 2020). This may, in part, be because farmers face a range of economic and policy pressures from the whole food supply chain, which may incline them towards less stringent nutrient management strategies (e.g., production contracts may restrict farmers' ability to adopt alternative production practices) (Hendrickson & James, 2005; Sheriff, 2005). Expanding policy, sectoral, and supply-chain boundaries have the potential to better address these indirect forces affecting N_r emissions and highlight policy interventions that have yet to be explored in relation to nutrient management. This could include anything from educating consumer to change their consumption patterns, to focusing on 'cluster points' in the food supply chain network where limited actors play a decisive role (e.g., supermarkets, fertilizer suppliers, etc.) (Galloway & Cowling, 2021; Kanter et al., 2019).

Incorporating nutrient reduction and management goals into policy and economic sectors not traditionally focused on nutrient management is a form of 'policy integration'. Policy integration is a proposed solution to the problem of traditional specialised policy measures not adequately addressing issues that transcend the boundaries of established institutional and political responsibilities. Policy integration attempts to ensure that there is consistency in addressing an issue across a variety of policy sectors and government agencies (Meijers & Stead, 2004). The concepts of "Health in All Policies" and "Environmental Mainstreaming" are examples of policy integration where policymakers have aimed to create interdependency and coherency between different policy domains (Tosun & Lang, 2017). While nutrient policy integration is a comparatively new scholarly discussion it is seen as way to potentially achieve multiple nutrient management objectives simultaneously, reduce policy transaction costs, and increasing the likelihood that governments' nutrient goals are met (Persson & Runhaar, 2018; A. L. Yang et al., 2022). I therefore apply this theme in my policy analysis in this thesis (chapter 5).

Understanding the landscape of existing policies is the first step in discussing new avenues for nutrient policy integration. Exploring the specific effects of nutrient policies has so far been beyond the scope of most nutrient accounting assessments and nutrient budget studies to date (Kanter, Chodos, et al., 2020; Kanter et al., 2019). Two recent studies have helped to establish a baseline for evaluating existing N policies, one which assessed national and regional N-related environmental legislation using the ECOLEX (www.ecolex.org) database (Kanter, Chodos, et al., 2020) and one which focused on South Asia which collected a broader range of policies beyond legislation (A. L. Yang et al., 2022). Both studies found a lack of integration across sectors and environmental concerns. While this is an important step in assessing nutrient policies, neither of these studies aimed to examine connections between existing policies, nor did they include phosphorus. In this thesis, I therefore turn my attention to this gap and the context of Canada.

Assessing connections between policies is time consuming and labour intensive, requiring researchers to read through large quantities of texts. With advances in natural language and text processing we can now speed up the process of identifying connections between documents. One such method that I explore in this thesis for its potential to provide insights into policy connections is semantic network analysis (sometimes referred to as text network analysis). Semantic network analysis is a combination of qualitative semantic analysis based on human interpretation of meaning, and quantitative network analysis which uses algorithms to calculate metrics of a given network (hubs, clusters, etc.). This approach has the benefit of fast automated processing of large amounts of text data (which a person cannot easily do) and meaning exploration (which a computer cannot easily do). In other words, the network analysis provides structural insights which may then be used as a starting point for more detailed exploration (Drieger, 2013; Paranyushkin, 2011).

In semantic network analysis, a network is created where texts are 'nodes' linked by 'edges' which are common words shared between texts. This approach is particularly useful in exploring integration in complex policy environments as it can identify 'communities', or common topics of similar texts, when there are more relations between texts within the communities than between communities (Newman, 2006). Perhaps more interestingly, semantic network analysis enables the identification of texts that are acting as 'bridges' creating unique connections in the network, and 'hubs' that are particularly strongly connected within the policy network (Burt, 2004; Drieger, 2013).

Semantic networks have been used extensively in research across multiple disciplines, especially in analysis of political discourse and social media (e.g., Bail, 2016; Kang et al., 2017; Radicioni et al., 2021; Shim et al., 2015). Some work has been done on environmental policy links (Bayarsaikhan et al., 2022) and measuring interactions between the Sustainable Development Goals (SDG's) (Fariña García et al., 2021; Weitz et al., 2018), however, to my knowledge, semantic network analysis has not yet been applied to examine networks of nutrient policies.

2.4 The Canadian context

In this literature review I have identified three gaps in our understanding of drivers of N emissions: subnational variation in N footprints, socio-economic drivers of whole-economy N_r emissions, and assessing integration potential in existing N policies. Canada provides an illustrative case study to examine these three facets of N_r accounting because it is a large, geographically, and economically diverse country allowing for a comparison of varied drivers at the subnational level. Figure 2.2 shows an example of this geographic diversity from a biophysical perspective using Ecozones, areas characterized by distinctions in climate, physiography, soil, vegetation, and fauna (Wiken et al., 1996). The following section provides a summary of N accounting research in Canada especially as it pertains to the three identified research gaps.

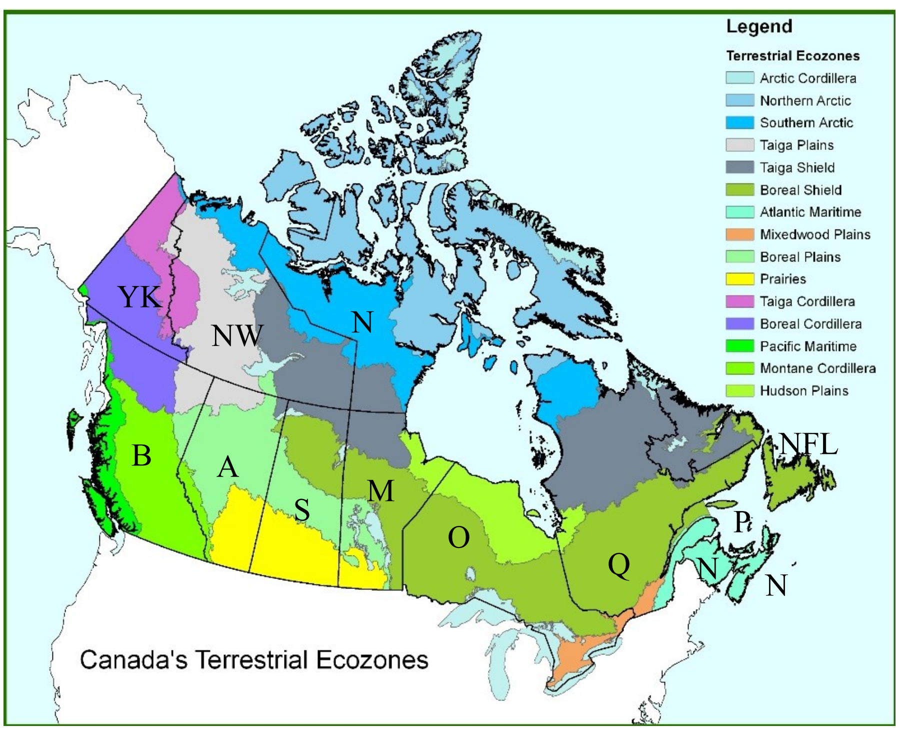

Figure 2.2 An example of Canadian geographic heterogeneity shown by the terrestrial ecozones across the 10 Canadian provinces (British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland and Labrador) and the 3 territories (Yukon, Northwest Territories and Nunavut). Figure from Natural Resources Canada (2013).

I am aware of two major national N budgets studies conducted in Canada to date. The first estimated major N flows and stores across Canadian urban areas, forests, water bodies and agricultural zones in 2007 (Clair et al., 2014). The second estimated changes in agroecosystem N between 1996 and 2016 (Karimi et al., 2020). Clair et al. showed that major anthropogenic sources of N_r emissions to the environment included NO_x from transport, and NH_3 and runoff from agriculture. Canada was also a major exporter of N_r in through food, hydrocarbons and fertilizer (Clair et al., 2014). Karimi et al. (2020) estimated crop NUE in Canada to be ~51% and agroecosystem NUE (crop and livestock N_r harvested / N_r inputs) to be ~60%, both in 2016. While NUE improved between 1990 and 2016, due to higher total N_r inputs the total N_r potentially lost to the environment through Canadian agriculture also increased during this time (Karimi et al., 2020).

The Government of Canada also has several pollution inventories and models that track estimates of various N_r emissions across Canada at a provincial (or finer) spatial scale. The Residual Soil Nitrogen (RSN) and Indictor Risk of Water contaminant – Nitrogen (IROWCN) models estimate N inputs, outputs, and leaching losses from agricultural land in Canada at the Soil Landscape of Canada scale (De Jong et al., 2009; Drury et al., 2007), the Air Pollutant Emissions Inventory (APEI) tracks NO_x and NH_3 emissions (Environment and Climate Change Canada, 2021b), and the Greenhouse Gas Inventory reports on N_2O (Environment and Climate Change Canada, 2021a). These inventories often reflect trends in individual species of N_r across provinces, following geographic patterns in agriculture and industry, as well as biophysical conditions including climate (Figure 2.2). For example, the majority of beef cattle, wheat, barley and canola production in Canada occurs in the Prairie provinces (Alberta, Saskatchewan and Manitoba), while most dairy, swine, poultry, corn and soybean are produced in eastern Canada (primarily in Ontario and Quebec). So, while the RSN show pockets of high (and increasing) soil N on a lot of agricultural land across Canada, this translates to higher NH_3 emissions in Alberta and Saskatchewan because of their dry prairie climate (Environment and Climate Change Canada, 2020a) whereas the risk of N leaching is much higher in Quebec due to wetter soil conditions (De Jong et al., 2009; Drury et al., 2007; J. Y. Yang et al., 2014). N_2O from manure management and agricultural soils is also highest in provinces with strong livestock and agriculture sectors (Alberta, Saskatchewan, Ontario and Quebec) (Environment and Climate Change Canada, 2021a, 2021b).

However, while there are individual inventories for N_r emissions across Canada, there has been no holistic assessment into the drivers behind increases or decreases in those emissions. For example, no N footprint has been estimated for Canada, but there has been some work done to link N emissions to consumption demand. Sheppard & Bittman (2015) estimated national agricultural NH_3 emissions linked to per person domestic consumption of food and to agricultural exports from Canada between 1981 and 2006. They found that shifts in the Canadian diet, with more protein being consumed but with less protein coming from beef, resulted in per person diet related NH_3 emission decreasing 20%. However, because the Canadian population increased and meat and egg exports increased, total national NH_3 emissions increased over the study period. They hypothesized that the effect of increased consumption and exports would exceed any decrease in emissions from improved best management practices at the producer level (Sheppard & Bittman, 2015). There has also been one Canadian study to date that used decomposition analysis to examine changes in energy use and greenhouse gases in the industrial sector (including N_2O), which showed that increased output was the biggest contributor to increases in industrial GHG emissions (Talaei et al., 2020).

In terms of the state of nitrogen policy in Canada, or nutrient policy in general, there have been attempts to create nutrient-focused legislation that directly addresses nutrient management (e.g. the Nutrient Management Act passed in Ontario in 2002). However, I located no published overviews of Canadian nutrient policies, although 74 nitrogen-related policies from Canada were identified in the global overview by Kanter et al. (2019).

2.5 Literature Review Conclusions

In this literature review I have highlighted the complexity of the nitrogen biogeochemical cycle and the intricacy of the anthropogenic drivers that are causing negative environmental outcomes. I identify two major gaps in our understanding of socioeconomic drivers of N_r emissions: the role of geographic variation in N footprints, and assessments of whole-economy N_r emissions. My review also highlights the fact that the N_r policy landscape is generally poorly understood. Better understanding these three areas will improve our ability to suggest N_r pollution reduction strategies. Furthermore, my review shows the importance of addressing these knowledge gaps in a holistic manner: accounting for multiple types of N_r emissions from different sources and impacting different concerns. Finally, I reviewed some key examples of large-scale (provincial and national) N research in Canada and demonstrated why it is a strong case study to use to examine these three gaps in the nitrogen research more broadly.

Therefore, my thesis aims to address these gaps by: 1) developing a new national N footprint model for Canada that takes into account subnational variation in consumption-oriented drivers, 2) synthesizing multiple sources and types of N_r emissions across Canada and decomposing the effect of socioeconomic drivers, and 3) assessing the nutrient policy landscape in Canada using semantic network analysis. All three approaches aim to show how drivers vary geographically and temporally and identify options for innovative interventions to reduce N_r pollution.

Preface to Chapter 3

Chapter 3 addresses my first research question regarding how consumption-oriented Nr drivers vary with sub-national geographic setting, with a focus on the Canadian context. As outlined in my literature review, better understanding the consumption-oriented drivers of Nr emissions is important for management of Nr emissions, and there has been increasing interest in estimating N footprints to highlight consumers' role in driving Nr emissions. However, current footprints are often calculated as a national average, which can obscure important local/regional variations. Estimating sub-national footprints is especially crucial to reflect the socioeconomic and geographic variation in a country as large as Canada, where variability between provinces could provide insight into potential strategies and interventions to reduce Nr emissions. Estimating additional national and sub-national virtual nitrogen factors (VNFs) for food production can also enable improved accounting of international N footprints, especially for countries that import goods from Canada.

Chapter 3 presents the development of a new nitrogen footprint model for Canada that incorporates provincial differences in consumption, food production, and wastewater treatment. I show that provincial total per capita N footprints vary widely, with most variation across provinces occurring because of differences in energy sources and industry related to fossil fuel combustion. This analysis also demonstrates the challenges of attributing N_r emissions in export-oriented economies. It provides novel insights on sub-national drivers of Nr emissions, emphasizing the need to consider how heterogeneous geographic contexts contribute to national N footprints.

This chapter was published in *Environmental Research Letters* in September 2021. The format has been modified to be consistent with the rest of the thesis. All references cited in Chapter 3 appear at the end of the chapter. Due to a journal production issue, some figures appear aesthetically differently than the published versions; I have retained the intended display here.

Chapter 3 Provincial nitrogen footprints highlight variability in drivers of reactive nitrogen emissions in Canada

Abstract

Nitrogen (N) footprints are one method to quantify consumer driven reactive nitrogen (N_r) emissions. Canada is a highly urbanized yet economically natural resource-dependent country, providing an illustrative case study to examine attribution of N_r emissions to per capita consumption, either domestically or abroad. Yet, considered only at the national scale, N footprints may obscure absolute and relative contributions of local drivers to N_r emissions. We apply a top-down N footprint approach drawing from national N budgets, emissions inventories, and agricultural statistics to estimate sub-national (provincial) drivers of N_r emissions across Canada. We calculate per capita provincial N_r footprints from four primary sectors in 2018: 1) crop production, 2) animal production, 3) wastewater treatment, and 4) fossil fuel burning. We estimate that Canada's total N footprint is 995.7 Gg N_r year^{-1}, which equates to an average per capita footprint nationally of 27.1 kg N_r capita^{-1} year^{-1}. The largest national contributions come from a few key (sub)sectors, including transport, beef consumption, and wastewater treatment. Provincial per capita N footprints vary widely, with the largest (Saskatchewan 50.3 kg cap^{-1} year^{-1}) more than double the smallest (Ontario 22.0 kg cap^{-1} year^{-1}). Most variation across provinces is due to the fossil fuels sector, including emissions from energy generation and the oil and gas industry. We therefore compare our top-down approach for the fossil fuels sector with bottom-up N footprints and territorial emissions methodologies. Per capita N emissions vary considerably across these approaches. For example, Alberta's per-capita fossil fuel N_r emissions are 45.9, 23.0, and 6.3 kg cap^{-1} year^{-1} using territorial, top-down, and bottom-up footprint approaches, respectively. This analysis demonstrates the challenges of attributing N_r emission for export-

oriented economies. Our study provides novel insights on sub-national drivers of N_r emissions, emphasizing the need to consider how heterogeneous geographic contexts contribute to national N footprints.

3.1 Introduction

Increasing the availability of reactive nitrogen (N_r, any form of nitrogen other than inert N_2) has been essential in growing enough food for the global population (Smil 1991). However, excess N_r results in negative environmental impacts such as eutrophication, smog, and greenhouse gas emissions. Anthropogenic sources of N_r now outweigh natural flows, with major inputs coming from synthetic fertilizers, increased biological nitrogen fixation, and fossil fuel combustion (Fowler et al 2013, Erisman et al 2008). In Canada there has been a steady increase in NH_3 emissions driven by fertilizer use and animal production (Environment and Climate Change Canada 2021a), agriculture accounts for 78% of national N2O emissions (Environment and Climate Change Canada 2021b), and elevated N_r concentrations remain a key water quality issue (Environment and Climate Change Canada 2012). While NO_x emissions are trending downward in Canada, further reductions are needed to reach goals set in the Gothenburg Protocol for transboundary air pollution (Environment and Climate Change Canada 2021a). Accounting tools that enable better quantification of N_r flows and inventories can inform policy and track the progress of mitigation efforts in order to balance future increases in N_r demands while mitigating negative N_r effects on society (Galloway and Cowling 2021, Houlton et al 2019).

Nitrogen (N) footprints are one method to quantify and communicate about excess N_r emissions. N footprints are a consumption-oriented approach that determines an entity’s contribution to N_r release due to activities within a defined boundary such as a country (Leach et al 2012), city

(Dukes et al 2020), or institution (MacDonald et al 2020). Leach et al. (Leach et al 2012) developed the first national-scale N footprint model for the United States, the N-calculator, in 2012, and recently updated their N footprint of food production (Leach submitted). A number of national N footprints have been calculated for other countries using adapted versions of this model, including the UK, Australia, Austria, Egypt, Tanzania and Japan (Liang et al 2016, Shibata et al 2014, Stevens et al 2014, Pierer et al 2014, Hutton et al 2017, Elrys et al 2019). Other top-down models have been used to calculate national N footprints for China, the European Union, and Japan (Gu et al 2013, Shindo and Yanagawa 2017, Leip et al 2014), and the N footprint of global trade has also been estimated by using multi-region input-output models (Oita et al 2016). Key drivers identified in these N footprint studies include the disproportionate impacts of the production and consumption of animal products (particularly beef), wastewater treatment, and the use of coal as an energy source (Leach et al 2012, Liang et al 2016, Shibata et al 2014).

Based on the key drivers identified in past studies, N footprints are typically broken down into two main components: N_r emissions related to food production and consumption (including wastewater) and N_r emissions related to fossil fuels (including transportation and energy generation) (Liang et al 2016, Shibata et al 2014). To account for N_r emissions associated with food production, N footprints include 'virtual' (or 'embodied') nitrogen: the total losses of N_r to the environment resulting from the production of food, but not contained in the consumed product (Galloway et al 2007). Estimating virtual N emissions as part of a food N footprint therefore commonly uses virtual nitrogen factors (VNFs): the ratio of N_r loss to the environment during the production and processing of a food item, compared to the weight of the final consumed product (kg N kg food^{-1}) (Leach et al 2012, Leip et al 2014). Since detailed VNFs are currently unavailable for many countries, some studies have used VNFs from the U.S. as proxies (Shibata et al 2014, Stevens et al 2014, MacDonald et al 2020). Estimating additional national and sub-national VNFs can therefore enable improved accounting of international food N footprints, for example, due to trade.

Previous country N footprints have typically been reported as national average per capita values. However, N_r flows and the relative importance of N footprint drivers (energy sources, food production and consumption patterns) can vary substantially across a nation (Liang et al 2018a). A single national average may obscure more local drivers of N footprints and therefore potential strategies to reduce N_r flows. Focusing on sub-national geographic contexts can highlight the differences in N_r production and consumption patterns within the same country, and is especially important to consider in large, geographically diverse nations, such as Canada.

Canada is therefore an illuminating case study to examine sub-national variation in both VNFs and the drivers of overall N footprints (Figure 3.1). Canada has a highly urbanized population (>80% urban (2019b) and is the 2nd largest country in the world by area, yet one of the least densely populated. Agriculture and fossil fuel production are important economic drivers in Canada but differ in relative contribution to gross domestic product (GDP) by province. For example, the oil and gas industry is 25% of the province of Alberta's GDP, but only 5% of Canada's overall GDP (Statistics Canada 2021h). Similarly, agricultural production is not evenly spread across the country. For example, Saskatchewan produces over 50% (by weight) of several of Canada's major field crops (lentils, Canola, oats and wheat) (Statistics Canada 2021e), while 30% of the Canadian hog population is in Quebec (Statistics Canada 2021c). Canada is a major exporter of many of these agricultural products, but given its northern climate, also relies on imports for several types of foods, including tropical fruit and rice (Statistics Canada 2021a). In particular, Canada-U.S. food trade is one of the largest trade relationships in the world (MacDonald et al 2015).

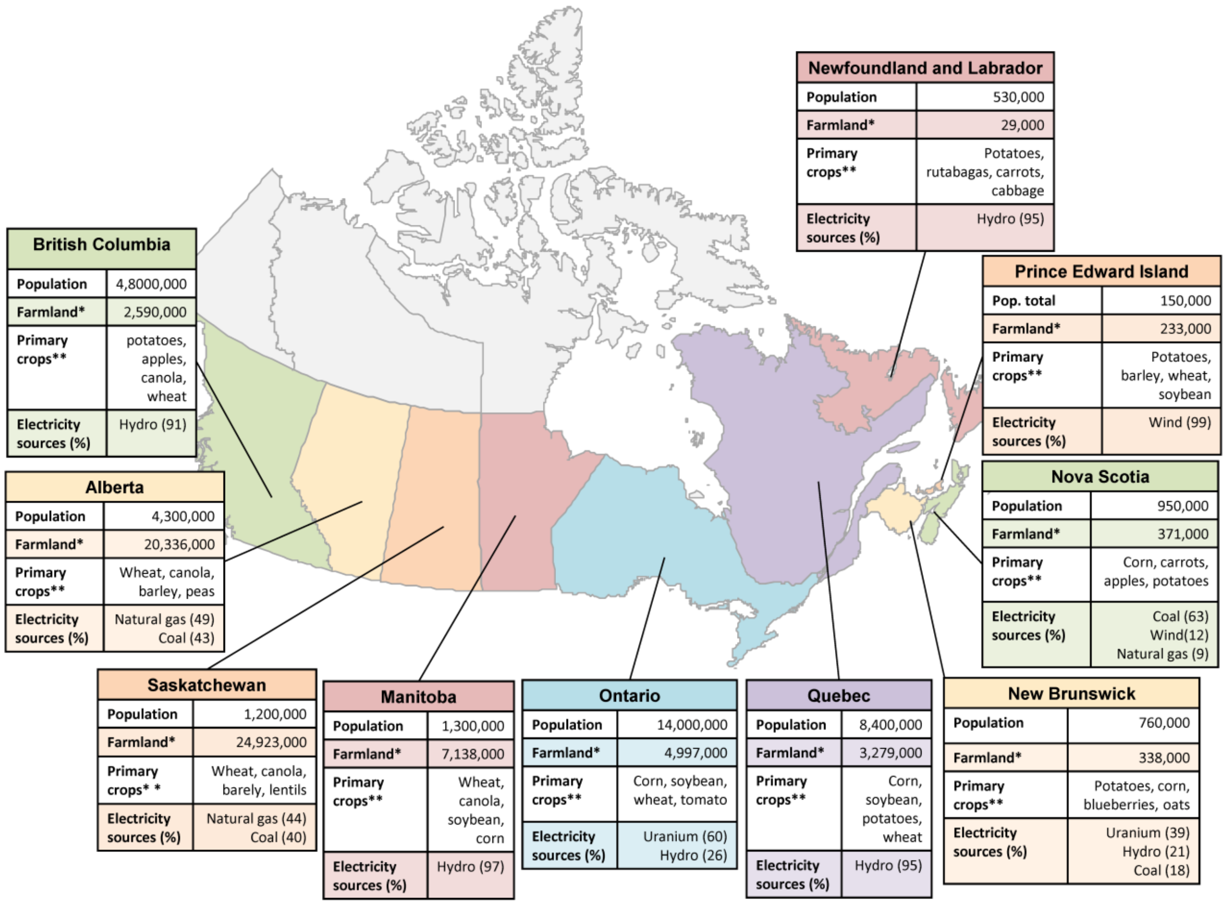

*Figure 3.1 Overview of the 10 Canadian provinces in terms of population, agricultural and energy characteristics that affect N footprints. Data from the 2016 Canadian Census (Government of Canada 2017), various Statistics Canada surveys and the National Energy Board of Canada (Canada Energy Regulator 2021). *Farmland is reported in hectares, including pasture and fallow. **Primary crops are listed by relative production (tonnes), excluding tame hay and corn for silage.*

Currently, no large-scale N footprint studies have focused on the Canadian context. However, several previous national studies have conducted N accounting: for example, the Residual Soil Nitrogen Indicator (RSN) and Indicator of Risk of Water Contamination by Nitrogen (IROWC-N) models developed by Agriculture and Agri-food Canada (AAFC) include mass-balance agricultural nitrogen budgets to estimate soil N losses from Canadian agriculture in 2001 (Yang et al 2007, De Jong et al 2009). Similarly, Karimi et al (2020) calculated an updated national agricultural N budget for Canada in 2020. A comprehensive Canadian N budget study was also conducted by Clair et al in 2014, which included N flows for both natural and human-dominated ecosystems. In this study we develop an N footprint model to account for N_r emissions released in Canada due to Canadian consumption and economic activities. We estimate the total (in Gg N_r year $^{-1}$) and per capita (kg N_r capita^{-1} year $^{-1}$) N footprints at the national scale for Canada and separately for each of Canada's 10 provinces for a three-year average around 2018. Our N footprint follows a top-down approach that captures N_r emissions from a variety of economic activities and sectors, encompassing both individual consumption patterns and broader societal activities. We expected that the nitrogen footprint of each province would vary given different underlying geographies and contexts. The specific objectives of this study are to:

1) estimate domestic virtual nitrogen factors (VNFs) nationally and sub-nationally (provincially) for food produced in Canada as part of the food N footprint;

2) estimate a domestic N footprint comprising four major driver sectors for Canada and its 10 provinces; and

3) compare variation in the drivers across N footprint sectors sub-nationally (by province).

3.2 Methodology

Our N footprint model accounts for N_r emissions (N2O, Nox, NH3, NO-3, NO-2, standardized as kg N) related to Canadian consumption, as well as fossil fuel burning associated with domestic economic activities (Table 3-1). Consumption activities include eating food, household utilities, and transportation. Emissions from economic activities that benefit Canadians include the oil and gas industry and manufacturing, although these subsectors may be export-oriented with final products consumed outside Canada (see section 3.2.5). We divided the N footprints into four driver sectors: N_r emissions from 1) crop production, 2) animal production, 3) wastewater treatment and 4) burning fossil fuels (Figure 3.2). To account for temporal variation, each N footprint is the average of three years (2017, 2018 and 2019), which are also the most recent years with available data for all relevant sectors. Our model was written in R v.4.0.4 (R Core Team 2021) and all datasets used in this study, as well as related equations and code for the data preparation and analyses, are available online (see Data availability statement).

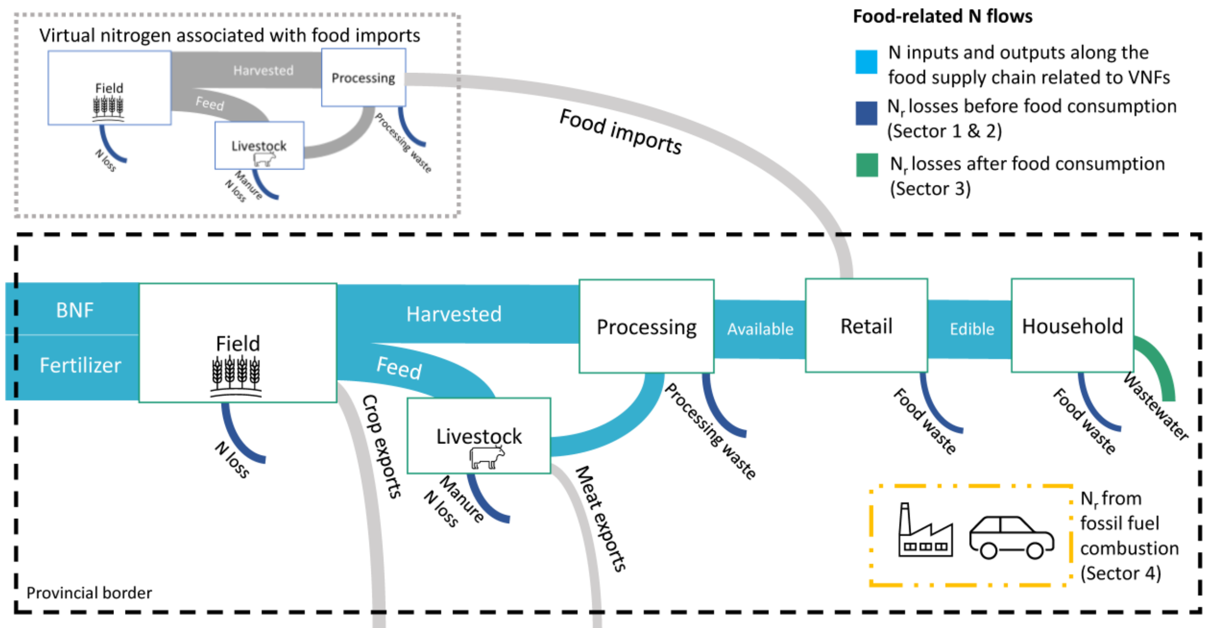

Figure 3.2 Diagram illustrating the key components of our top-down N footprint model. N footprints were estimated for each province, broken down into N_r losses due to food production (sector 1 crop production and sector 2 animal production), N_r losses after food consumption (sector 3 wastewater treatment) and N_r release from burning fossil fuels (sector 4). For food production, we estimated potential N_r losses at each step of the food supply chain (field, processing, etc.). To assess uncertainty around the impact of food trade, we performed a sensitivity analysis using different assumptions on origin of food consumed in a province (see Figure 3.6).

Table 3-1: Overview of N flow methodologies and data sources for the N footprint model in this study

Sector	N flows	Methods	Data and assumptions	Source
1 & 2 VNFS	*Fertilizer*	Fertilizer sales, adjusted by crop recommended fertilizer rates and crop areas	Fertilizer shipments to Canadian agricultural markets Crop areas Provincially recommended fertilizer rates (RSN model)	Statistics Canada (2020b) Statistics Canada (2021e, 2021f, 2021g, 2021d) Yang et al (2007)
	BNF	Crop area x crop BNF rate	Crop area and production Canadian BNF rates	Statistics Canada (2021e) Karimi et al (2020)
	N content harvested crops	Crop production x N content of crop	Crop production N content of crops	Statistics Canada (2021e, 2021f, 2021g, 2021d) Karimi et al (2020)
	N content livestock feed	Animal population x feed composition and rates x N content of feed	Livestock populations Provincial feed composition and rates (from farm livestock surveys)	Statistics Canada (2021c, 2020e, 2020c) Sheppard et al (2015)
	N content of slaughtered animals	Animal population x % slaughtered x N content of whole animal	Livestock populations Slaughter rate estimates Animal N content	(Statistics Canada 2021c, 2020e, 2020c) Sheppard et al (2015) Karimi et al (2020)
	N content of animal products	Milk & egg production x N content	Milk and egg production N contents	(Statistics Canada 2021b, 2020d) Karimi et al (2020)
	N loss during manure storage	Manure N production x % animal populations on pasture x % N remaining after storage co-efficient Manure N production = N content of feed* – N content of animals slaughtered* and animal products*	Provincial animals on pasture and manure storage coefficients (from manure management surveys)	Huffman et al (2008)
	Denitrification & leaching	N applied to soil – denitrification x provincial leaching coefficients N applied to soil = (Fertilizer* + BNF* – N content harvested crops*) + (N manure production* – N loss storage*)	10 % of N to soil is denitrified, 1:1 ratio N_20 to N_2 Provincial leaching coefficients (IROWC-N model)	Yang et al (2007) De Jong et al (2009)
	Aquaculture	Feed weight = aquaculture production x feed conversion ratio	Aquaculture production Feed conversion ratio: 1.1 Feed is 70% soy N excretion rate: 32 g N/ kg growth	Statistics Canada (2020b) Canadian Aquaculture Industry Alliance reports Reid (2007)
	Food processing and waste	(Unprocessed food production kg x N content) – (Processed consumed food weight x N content) Processed consumed food weight = unprocessed food production weight x food loss coefficients	Food loss coefficients N content unprocessed N content processed	USDA (2020) Karimi et al (2020) Canadian Nutrient File(Health Canada 2012), Lassaletta et al (2014)
1, 2 & 3	*Household food consumption*	National food availability statistics adjusted by household food consumption	Food available in Canada Household food consumption from 24-hour dietary recall	Statistics Canada (2021a) CCHS-N
3	*Wastewater treatment*	(N excreted x wastewater treatment N removal coefficients) + N_r emissions from incineration	Wastewater aqueous N removal coefficients Wastewater treatment coverage Nr emissions incineration	Wastewater Treatment Reports (S3) Statistics Canada (2021i) GHG and APEI
4	*N from fossil fuels*	N_2O and NO_x emissions		GHG and APEI

*Estimated in a previous step. GHG: Canada's National Greenhouse Gas Inventory (Environment and Climate Change Canada 2020b), APEI: Canada's National Air Pollution Emissions Inventory (Environment and Climate Change Canada 2020a). CCHS-N: Canadian Community Health Survey – Nutrition (Statistics Canada 2007)

3.2.1 Food production and VNFs

We estimated VNFs at the national scale for Canada and separately for each of Canada's 10 provinces (the three northern territories were excluded due to limited data). Our study encompasses 45 crops, which we aggregated into 5 crop groups: 1) grains, 2) fruits, 3) vegetables, 4) roots, and 5) legumes (see Supplementary Information S1 for food groups). Animal product VNFs were calculated for beef, pork, chicken, fish, milk, and eggs. We estimated VNFs as the sum of apparent N_r losses along the food supply chain from agriculture, processing, and food waste per kg of food consumed. N_r losses for crops include potential losses on agricultural fields and due to food processing and waste. N_r losses for animal products include the virtual N due to animal feed, manure N_r loss, and food processing and waste (Figure 3.2).

At each step of the food supply chain, we estimated N_r release as the potential combined N_r losses to air and water (kg N). We estimated N_r losses as the difference between new N_r inputs and N_r outputs at a given step, and considered N recycling, leaching and denitrification (Table 3-1). We subtracted inert N2 from our emissions since our focus is on N_r.

3.2.2.1 Agricultural field losses

To estimate N_r release that occurs in the field we estimated the difference between key inputs of new N_r and outputs at the field level. Inputs of new N_r were synthetic fertilizer and biological nitrogen fixation (BNF) while the output was N uptake from harvested crops. From this net-N_r applied to soils, we then estimated N_r leaching and denitrification (Table 3-1). We did not include manure as an input in this step as it is a 'recycled' form of N, not new N_r, nor did we include atmospheric N_r deposition to avoid double-counting and N_r from other sources (e.g. fossil fuel emissions). Our handling of manure N and related losses is expanded on in section 3.2.2.2 on the animal VNFs below.

To estimate fertilizer N inputs by crop we followed the approach used by Yang et al (Yang et al 2007). We disaggregated total provincial N fertilizer sales for agricultural use based on crop areas in each province and the provincially recommended N application rate for each crop. While our study includes 45 individual crops, this may not capture every possible crop receiving a portion of the total fertilizer used in each province. As a result, the fertilizer N applied to our study crops is likely a slight overestimation. BNF was calculated by multiplying the N content of leguminous crops by the percentage that is fixed from the atmosphere. Values for N contents and BNF rates were taken from Karimi et al (2020). Crop N removal was estimated by multiplying crop dry-matter production from annual surveys from Statistics Canada (see Table 3-1), by total crop N concentrations, including the harvested portion, residues, and root growth. Total crop N concentrations were taken from data published by Karimi et al (2020).

Estimates of denitrification and leaching at the national scale are uncertain due to high spatiotemporal variability. We therefore used the overall denitrification losses approach of Karimi et al (2020), and assumed that 10% of N contained in fertilizer and 10% of organic N remaining in soil from crop residues and roots are denitrified. Following the approach of Agriculture and Agri-food Canada's (AAFC) Residual Soil Nitrogen (RSN) model we assume that there is a 1:1 denitrification ratio of N20 to N2 (Yang et al 2007). We then estimated leaching values by applying an average provincial leaching co-efficient derived from AAFC's Indicator of Risk of Water Contamination by Nitrogen (IROWC-N) (De Jong et al 2009).

3.2.2.2 Animal feed and manure

For animal products, we accounted for N losses associated with feed production and the N_r released from manure during storage and once applied to soil. Virtual nitrogen for animal feed was estimated by multiplying the approximate weight and type of feed consumed per head of animal by the relevant crop VNF, including feed from forage and pasture (Table 3-1). Data on Canadian livestock feed mix and amounts were taken from Canadian feed surveys and models by Sheppard and Bittman (2015). VNFs for feed crops and fertilized pasture were calculated assuming all N_r losses happen on the field. Forage VNFs were weighted by the ratio of managed to unmanaged pasture, given the disparities in N fertilizer use for these systems. There is potential overlap in how we attribute emissions from animals that produce both meat and other products (i.e. layer poultry and dairy cows). However, in their study of ammonia emissions from Canadian livestock, Sheppard and Bittman found that 97% of dairy cow emissions could be attributed to milk production, and 93% of layer emissions could be attributed to egg production (Sheppard and Bittman 2015). Therefore, we estimated beef VNFs using only beef cattle, milk from dairy cattle, chicken meat from broiler chickens, and eggs from layer chickens.

We assumed total manure N_r production for a given population of animals is equal to the difference between N consumed yearly through feed and the N contained in animals removed for slaughter (Puckett et al 1999). Only partial data is available at the provincial scale on number of animals slaughtered, so we applied estimates on the fraction of animal populations that are slaughtered annually (Sheppard and Bittman 2015) to provincial animal populations. We cross-checked our estimates with national slaughter statistics, and they were within 10% for cattle, and 5% for hogs and chickens. Animals slaughtered were multiplied by average animal weight at slaughter (Sheppard and Bittman 2015) , and animal N concentrations (Karimi et al 2020) to estimate N removal.

To estimate potential N_r losses from manure that is applied to soil, we assumed manure produced by pasture-grazed animals was deposited directly on pasture, and manure from housed livestock animals is stored before being applied to crops. Provincial distributions of manure management practices came from Huffman et al (Huffman et al 2008). We multiplied our estimated manure production by coefficients for Canadian animal populations raised on pasture, and percentages of manure N_r remaining after storage (volatilization) losses for each management type (Huffman et al 2008). As with our crop VNFs, we assumed that 10% of N in manure applied to soil is denitrified (Karimi et al 2020) at a 1:1 N_20 to N_2 ratio (Yang et al 2007), and then applied average provincial leaching values (De Jong et al 2009). The remaining manure N_r is what we consider "potentially recycled N_r", which is therefore omitted from losses.

Feed and manure N from farmed fish production were estimated using a slightly different method than other animal products. As 70% of aquaculture in Canada (by weight) is salmon (Statistics Canada 2020b), we used salmon as a proxy for all aquaculture production in Canada. To estimate virtual N associated with aquaculture feed, we used data from Canadian salmon farming reports, which suggested that approximately 70% of salmon feed is soy; we inferred that the remainder was from fish meal and oil from forage fish, which we assumed have negligible new anthropogenic N_r inputs and are therefore omitted from our VNFs. We used a feed conversion ratio of 1:1 to estimate amount of feed consumed by fish annually (Canadian Aquaculture Industry Alliance n.d.) and an N excretion rate from farmed salmon of 32 g N kg^{-1} of growth (Reid 2007).

3.2.2 Food origin scenarios

We examined different scenarios to assess how assumptions and uncertainties about geographic food sourcing affect our provincial food N footprints. In our main analysis, we apply national weighted average VNFs based on the share of food production coming from each province. This assumes food is sourced nationally in proportion to provincial production. For example, the Canadian average VNF for beef is heavily weighted towards Alberta's beef VNF since this province produces the most beef in Canada. For context, Canada produces far more beef, pork and chicken domestically than it imports (imports account for 18%, 11%, and 13% respectively of the total supply of these foods) (Statistics Canada 2020a).

We applied two scenarios to examine uncertainty using alternative VNFs for each province. First, we used province specific VNFs, assuming food is produced and consumed in the same province. If provincial VNFs were unavailable (e.g., provincial fruit VNFs could not be calculated for Newfoundland and Labrador due to data availability), we used the Canadian weighted average VNF. Second, because the United States is Canada's largest agricultural trading partner (FAOSTAT 2021b), we also estimated each provinces' food N footprint when using national weighted average VNFs for the U.S. from Leach et al (submitted), representing a scenario where food consumed in each province is sourced from the U.S.

3.2.3 Food consumption

Previous N footprint studies have typically used national average diets to estimate food intake, mainly from FAOSTAT (Leach et al 2012, Shibata et al 2014). For Canada, national food availability data from Statistics Canada (kg person^{-1} year^{-1} adjusted for retail and household losses) (Statistics Canada 2021a) are available. Given the objectives of our study, we use a simple approach to incorporate variations in provincial diets into our model. First, to assess whether there are significant differences in food consumption patterns between provinces, we performed a Kruskal-Wallis statistical analysis using data from the 2015 Canadian Community Health Survey-Nutrition (CCHS-N). The CCH-S is a national nutrition and health 24-hour average food intake recall survey by Statistics Canada and Health Canada that included >35,000 respondents. (Statistics Canada 2007) Several food groups, including beef, were consumed in significantly different quantities ($p < 0.05$) between provinces. However, when compared to national food availability data from Statistics Canada, the CCHS-N survey appeared to underrepresent absolute per capita meat consumption (in kg). Therefore, we scaled the national food availability values to the provincial level by using the relative provincial consumption values from the CCHS-N survey (see S2 for more detail). Consumed food weight was multiplied by the respective food N contents from the Canadian Nutrient File from Health Canada (2012) to estimate per capita N consumed.

3.2.4 Wastewater treatment

We estimated potential N_r loss during wastewater treatment as the sum of N_r released to water and air during and after treatment as well as N_r emissions from waste incineration. To estimate influent N_r to wastewater, we assumed all food N consumed by the population of each province is excreted (Liang et al 2018b). To estimate aqueous N_r removal we used N_r influent and effluent measurements from wastewater treatment plants representing the three treatment levels in Canada (primary, secondary, and tertiary) as proxies (see S3). Aqueous N_r removal was estimated as the difference between total N_r (total Kjeldahl nitrogen, nitrates, and nitrites) in influent and effluent. We therefore assume that 75% of influent N_r is released to surface waters or groundwater under primary treatment, 66% after secondary treatment and 30% after tertiary. In the case of no treatment, which includes septic tanks, we assume that 95% of consumed N_r is released to water (Brandes 1978). Aqueous N_r removal was then weighted by the percentage of the population in a province that is served by each of three wastewater treatment levels using data from Statistics Canada (Statistics Canada 2021i).

We estimated gaseous N_r released as N_2O, NO_x and NH_3 emissions from wastewater treatment and waste incineration based on data from Canada's National Greenhouse Gas (GHG) Inventory, and from Canada's Air Pollutant Emissions Inventory (APEI). As with our agricultural estimates we assume a 1:1 N_2O to N_2 denitrification ratio. These atmospheric loss values include wastewater N_r from non-food sources (e.g. industry and other discharge), so they are likely proportionally larger than our estimates of N_r release to water, which are based on food N consumption.

The fate of remaining N_r after wastewater treatment (removed as biosolids or sludge and not incinerated) is uncertain. In our main analysis we assume 25% of this N_r is beneficially recycled. However, by some estimates, as much as 50% of wastewater biosolids may be recycled in Canada (Karimi et al 2020), with the rest being landfilled. Therefore, we performed a sensitivity analysis using a lower and upper bound of N_r recycling ranging from a low of 25% to a high of 50% 'beneficial' recycling to land (which lowers the N footprint).

3.2.5 Fossil Fuels

To estimate fossil fuel-related N_r emissions we use a top-down approach, summing data on provincial N_2O and NO_x emissions (the forms of N_r released by burning fossil fuels). Data were obtained from greenhouse gas and air pollutant inventories, which account for N_2O and NO_x emissions, respectively. We then categorized these emissions into 4 subsectors based on their sources: 1) energy generation (emissions from public electricity and heat production, as well as commercial, institutional, and residential stationary combustion) 2) transportation (emissions from aviation, rail, trucks, and other vehicles), 3) the oil and gas industry, and 4) other industry sources (stationary energy generation and other emission sources from construction, mining, and other manufacturing industries). The oil and gas industry form a separate category because we expected them to be large sources of N_r emissions in Canada. However, for an N footprint, not all oil and gas industry emissions should be attributed to consumption in Canada since most of the oil is ultimately consumed abroad. Therefore, we only include 15% of the total sector emissions as approximately 85% of oil is exported (Statistics Canada 2016).

3.3 Results and Discussion

We estimate that Canada's total N footprint is 995.7 Gg N_r year^{-1}, which equates to an average per capita footprint nationally of 27.1 kg N_r capita $^{-1}$ year^{-1} for the period around the year 2018. There are clear differences in total N footprints, per capita N footprints, and the main sources of N_r between provinces. Provincial N footprints vary from 3.5 Gg N_r year^{-1} (Prince Edward Island) to 311.8 Gg N_r year^{-1} (Ontario) (Figure 3.3A), the smallest and largest provinces by population, respectively. Saskatchewan has the largest per capita footprint at 50.3 kg N_r capita $^{-1}$ year^{-1}, and Ontario the smallest at 22.0 kg N_r capita $^{-1}$ year^{-1} (Figure 3.3 A, B). Major drivers across all provinces include transport, beef consumption and wastewater treatment (Figure 3.4 A, B). The contributions of fossil fuels to the per-capita footprints are strongly influenced by the presence of the oil and gas industry.

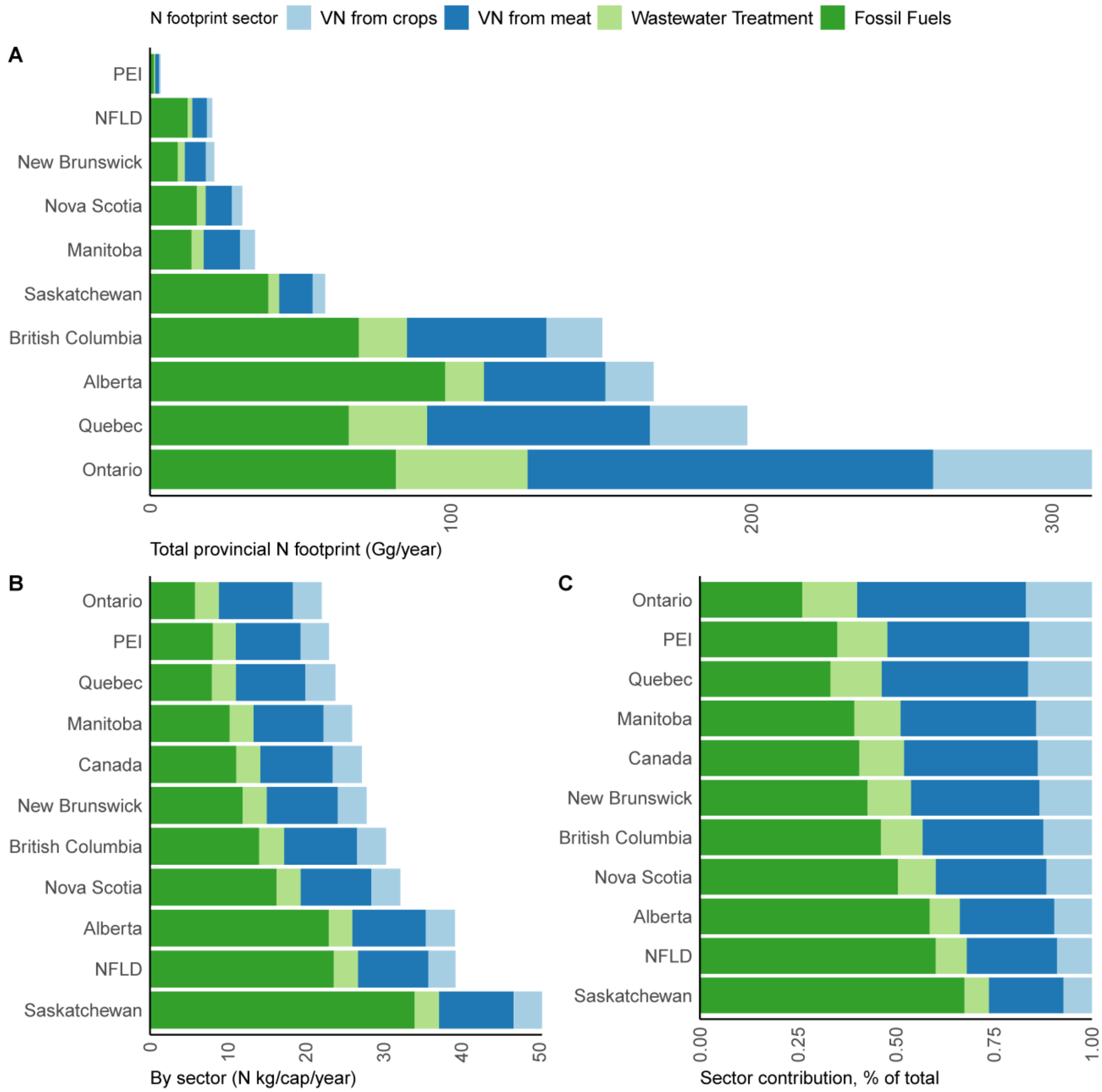

Figure 3.3 Total provincial N footprints by sector (A), per capita provincial N footprints by sector (B), and the relative contribution of each sector to a provinces' per capita footprint (C).

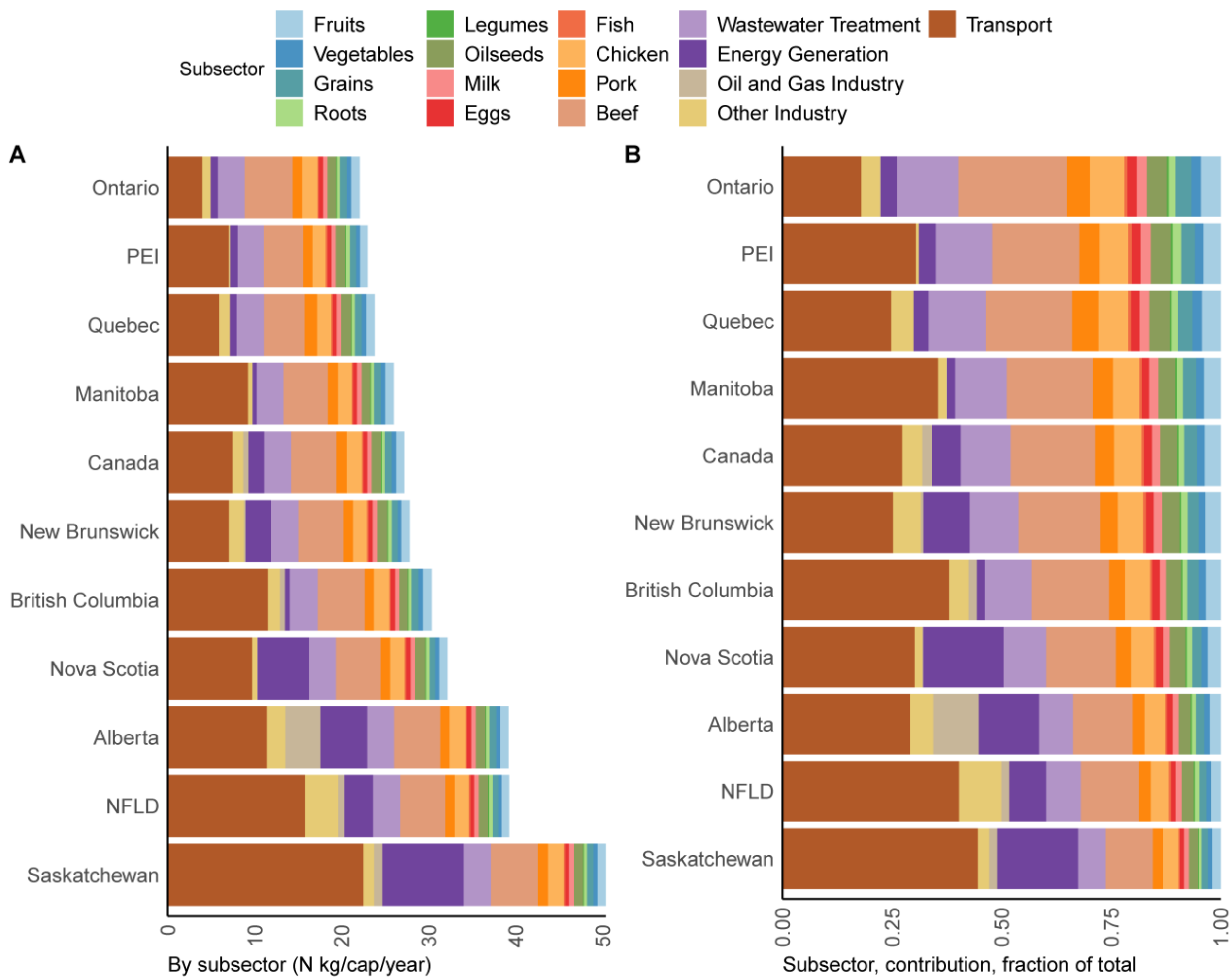

Figure 3.4 Per capita provincial N footprints by subsector (A), and the contribution of each subsector to each provinces' per capita footprint (B).

3.3.1 Food production and consumption

Diet is a major driver of N footprints in Canada. The average Canadian N footprint from food production is 12.9 kg N capita^{-1} year^{-1}, 50% of the total Canadian N footprint. However, in most provinces, other than Ontario and Quebec, less than 50% of the N footprint comes from food production. Ontario and Quebec are the two most populous provinces in Canada, and together account for nearly two-thirds of Canada's population (40% and 24% respectively). Therefore, the national weighted N footprint is disproportionately impacted by these provinces. Virtual nitrogen from meat production is a substantial contributor to N_r emissions across all provinces. Within the meat subsector, beef consumption is the largest driver. Beef consumption is the single largest overall driver of Ontario's, New Brunswick's, and Quebec's N footprints (5.4, 5.2, and 4.7 kg N capita^{-1} year^{-1}, respectively) and second largest in all other provinces except Alberta and Saskatchewan (Figure 3.4 A, B).

Our findings related to food production are broadly comparable to other N footprint studies. For example, Leach et al (submitted) estimated the food production N footprint for the U.S. to be ~26 kg N capita^{-1} year^{-1}. Beyond differences in models, there are notable disparities in diets between the U.S. and Canada. For example, FAO estimates suggest Americans consume more meat than Canadians (e.g. the United States has a beef supply of 37.16 kg capita^{-1} year^{-1} whereas Canada's is 26.78 kg capita^{-1} year^{-1} (FAOSTAT 2021c)). The difference in beef consumption alone could explain ~3kg capita^{-1} additional N in the U.S. N footprint as compared to Canada. We discuss other differences related to VNFs in the next section.

Virtual nitrogen factors

Beef, pork, chicken, have the highest average VNFs of all food groups, which is common among other studies and mainly due to relatively lower efficiency of converting feed crops into edible protein (Metson et al 2020). Crops tend to have lower VNFs than animal products, although there is a large range between provincial values (Figure 3.5 and S4). While differences in types of crops grown and farm N management affect the variability in provincial crop VNFs, environmental factors, such as leaching potential, also play a role. Wetter, colder provinces have higher leaching potential (De Jong et al 2009), which partially accounts for the higher VNFs for most crop groups in Newfoundland and Labrador, Nova Scotia, and New Brunswick.

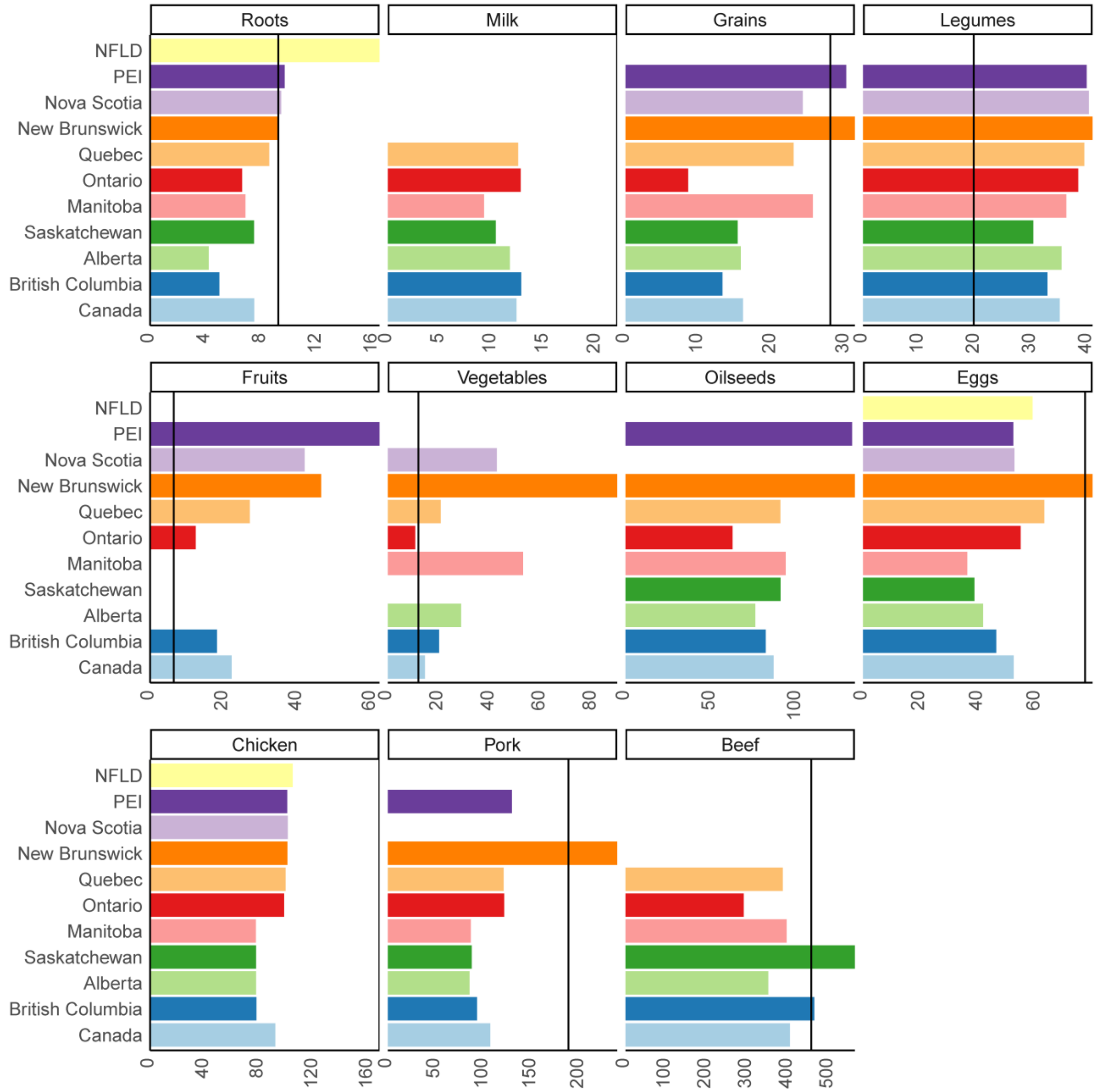

Figure 3.5 Provincial virtual nitrogen factors (VNFs, g N kg food^{-1}) for different food groups. The Canadian average is a weighted average of provincial VNFs weighted by production. Provinces with no VNF for a food group have a small number of producers and are censored in Canadian agricultural surveys. Vertical lines indicate U.S. VNFs (Leach submitted) for comparison. Plots are organized from smallest to largest VNF, and horizontal axis vary accordingly. Our VNF for fish is 60 g N kg food^{-1}, not shown here as it assumed to be the same across all provinces. NFLD: Newfoundland and Labrador, PEI: Prince Edward Island.

We compare our Canadian VNFs to findings for the U.S. from Leach et al (submitted) (see vertical lines in Figure 3.5) and find that they are of comparable magnitudes for most food items, especially beef (our average weighted Canadian beef VNF is 401 g N kg food^{-1}, the U.S. beef

VNF is 456 g N kg food^{-1} (Leach submitted)). Our VNFs for pork and chicken are about 45% lower than those for the U.S., while our Canadian fruit and vegetable VNFs tend be higher (Figure 3.5). These differences in the U.S. and Canadian VNFs are partly attributable to differences in crops considered in each food group (e.g. cereals in Canada include corn, rye, oats, triticale and wheat, whereas cereals in the U.S. include corn, wheat, and rice), and agricultural practices between the two countries, such as differences in crop fertilizer recommendation rates (e.g. Ontario, Canada recommends 135 lbs N/acre of corn (Ontario Ministry of Agriculture, Food and Rural Affairs 2018) whereas Minnesota, U.S. recommends 145-195 lbs N/acre (University of Minnesota Extension 2021)). Differences are also a reflection of methodologies, including data sources, N_r loss accounting, and livestock feed conversion efficiencies. For example, in our approach we use fertilizer sales data whereas Leach et al (submitted), used recommend fertilizer rates by crop and state mainly from university agricultural extension agencies.

Our VNF food origin scenarios resulted in a Canadian average food N footprint ranging from 12.4 kg N cap^{-1} year^{-1} (using provincial VNFs) to 16.7 kg N cap^{-1} year^{-1} (using U.S. VNFs) (Figure 3.6). The Canadian average is heavily weighted towards Ontario, which has roughly half of Canada's total population. This province has relatively low provincial VNFs for most food groups (Figure 3.5), resulting in a 37% increase in virtual nitrogen for the scenario assuming sourcing food from the United States (U.S. VNFs) over the scenario with local food sourcing (provincial VNFs) (Figure 3.6). However, seven out of the ten provinces have their lowest relative food N footprints when assuming food is consumed proportionally to overall Canadian production (Canadian VNFs), which is the approach we use in our main results (Figure 3.5). Since beef has a substantially higher VNF than other foods (four times that of pork, the next largest VNF), this was also strongly reflected in our food origin sensitivity analysis. In all scenarios and provinces 35-40% of virtual nitrogen was from beef consumption.

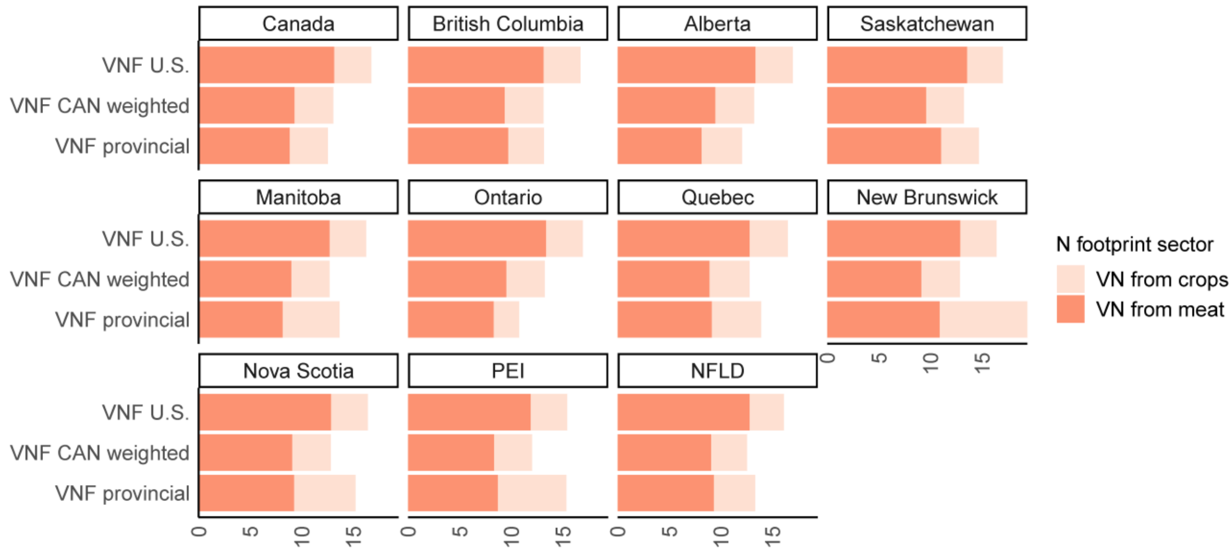

Figure 3.6 Sensitivity analysis using different VNFs to estimate national and provincial virtual nitrogen footprints (N kg cap^{-1} year $^{-1}$) from consumption of crops and animal products. We used VNFs assuming 1) all food consumed in a province is sourced in a province (VNF provincial), 2) all food is sourced proportionally to overall Canadian production (VNF CAN weighted), and 3) food is sourced from the U.S. (VNF U.S.). Where a province did not have a VNF for a specific food group (Figure 3.5), we used the Canadian weighted average for that food group instead.

Wastewater treatment

N_r release from wastewater treatment accounts for 3.1 kg N cap^{-1} year^{-1} of the Canadian average N footprint, which makes it the third largest driver of the national and most provincial N footprints. Nitrates and nitrites are not regulated at a federal level across Canada, and ammonia regulation varies by province (Oleszkiewicz 2015). Geographical proximity to the ocean may be reflected in wastewater regulation for relatively low-population density coastal provinces (Nova Scotia, New Brunswick, Prince Edward Island and Newfoundland) as well as British Columbia, which discharge primarily to coastal waters and have generally lower N effluent standards than interior provinces (Ontario, Manitoba, Saskatchewan and Alberta) (Oleszkiewicz 2015). Only ~30% of Canada's population is connected to municipal wastewater systems that receive tertiary treatment (the treatment level that may include biological nitrogen removal) (Statistics Canada 2021i).

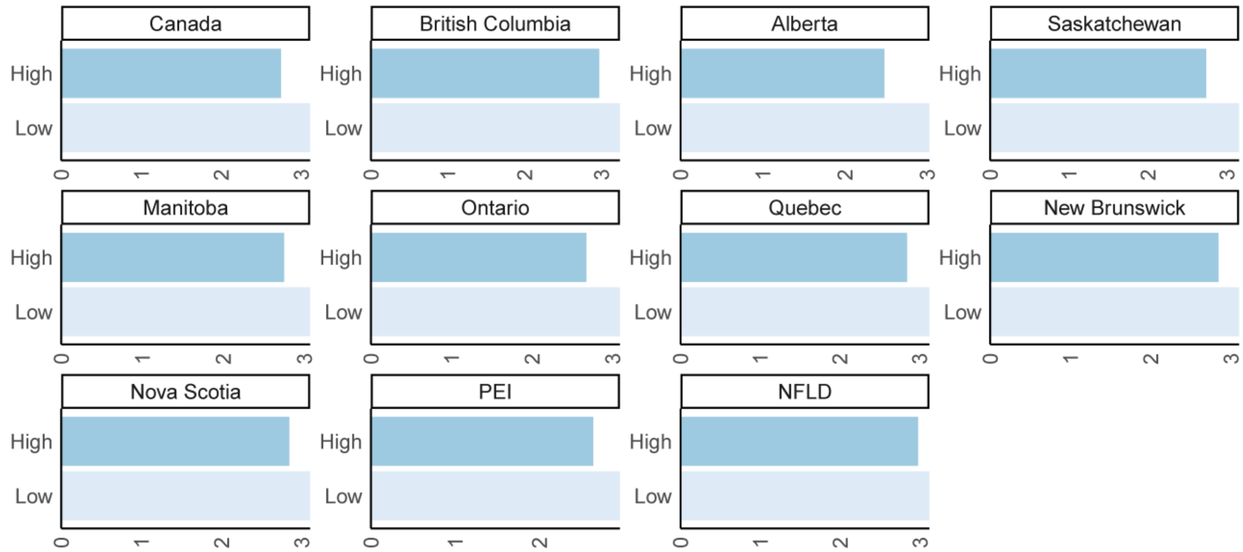

Figure 3.7 Wastewater sensitivity analysis examining different assumptions about recycling versus landfilling biosolids and sludge from wastewater treatment (N kg cap^{-1} year 1). High recycling assumes 50% of N removed during wastewater treatment is recycled, and low assumes 25% recycling.

Our wastewater treatment scenarios reflect the relatively low level of N_r removal in wastewater treatment across Canada: when using high (50%) and low (25%) N recycling scenarios, the average Canadian wastewater footprint decreases from 3.1 kg N cap^{-1} year^{-1} to 2.7 kg N cap^{-1} year^{-1} (+/- 13%). The largest variation was for Alberta (2.5-3.0 kg N cap^{-1} year^{-1}, +/- 17%), which is the province with the highest tertiary treatment coverage (84%). Conversely, in British Columbia only 10% of the population is covered by tertiary treatment, and it is also the province with the largest wastewater N footprint, varying between 3.1-3.2 kg N cap^{-1} year^{-1} (+/- 3%) for the high/low scenarios.

3.3.2 Fossil fuels

Burning fossil fuels accounts for 11.1 kg N capita^{-1} year^{-1}¬, or 40% of the average Canadian N footprint. Larger provincial fossil fuel footprints mainly coincide with the makeup of energy grids and the presence or absence of fossil fuel or other natural resource extraction. The average energy N footprint in Canada is 1.8 kg N capita^{-1} year^{-1} but varies considerably by province. In Nova Scotia, Saskatchewan and Alberta, 63%, 40% and 43% (Canada Energy Regulator 2021), respectively, of the energy grids are powered by burning coal (Figure 3.1). These three provinces have a combined average energy N footprint of 6.9 kg N capita^{-1} year^{-1}¬, whereas other provinces are powered primarily by renewables and nuclear energy and have an average energy N footprint of 1.4 kg N capita^{-1} year^{-1}.

N_r emissions related to transport are the largest portion of the fossil fuel N footprint sector in Canada (7.4 kg N capita^{-1} year^{-1} on average) and in six provinces (Figure 3.4). Canada is one of the least densely populated countries on the planet, has large distances between cities, cold winters, and a strong natural resource sector. This means Canadians drive more than in many other nations (on average Canadians drive ~15,200 km year^{-1} (Natural Resources Canada 2008), Americans, by comparison, drive ~13,500 km year^{-1} (United States Department of Transportation 2018)). In addition, heavy-duty (>3.9 tonne) diesel vehicles are a major contributor to transport emissions in several provinces, typically associated with trucking, mining and other resource extraction activities (Environment and Climate Change Canada 2020a). While resource extraction contributes to a province's economy and thus indirectly benefits Canadians, these activities may be associated with foreign exports and thus consumption activities abroad.

3.3.3 Attributing top-down N footprint emissions from fossil fuels

Our top-down approach to N footprints (national and provincial territorial emissions divided by population) differs from bottom-up N footprint studies, which estimate N emissions using personal consumption data (e.g. household electricity use, and personal distances driven or flown), multiplied by emissions factors (Leach et al 2012, Liang et al 2016, Shibata et al 2014, Pierer et al 2014). Our top-down methodology, drawing from territorial N emission datasets, therefore captures additional N emissions when compared to a bottom-up approach, particularly in the case of fossil fuels. Since some territorial emissions may ultimately be attributed to consumption activities in other countries, they should be discounted from our N footprint. However, the specific amount to discount is uncertain. For example, the APEI and GHG territorial inventories report N_r emissions for "aviation", which includes emissions associated with direct personal consumption (e.g., vacation flights), indirect consumption (cargo flights bringing in imports), and with exports (which should be excluded from an N footprint). A bottom-up approach only captures the emissions from direct personal consumption, whereas a top-down approach potentially captures emissions from all three areas.

To examine this uncertainty, we compared our fossil fuel N footprint results across these different approaches in our national N footprint, and for two resource-dependent provinces (Table 3-2). These two provinces produce most (~90%) of Canada's oil and gas (Statistics Canada 2016). Alberta alone produced 80% of Canada's total oil in 2019 (~200 thousand m^3). We approximated a bottom-up fossil fuel N footprint by including only categories from the APEI and GHG inventories that were similar to those in the N-Calculator (a bottom-up N footprint model) (Leach et al 2012), and a strictly territorial per capita N emissions estimate (including all categories with no adjustment for exports). The largest differences occur when discounting exports from the oil and gas industry in Alberta (the main approach we used in this study), and whether emissions from all forms of transport (like heavy machinery) are included in Saskatchewan.

Table 3-2 Per capita fossil fuel emissions from three methodologies, nationally and for two major oil and gas dependent provinces, Alberta, and Saskatchewan.

		Fossil fuel N-related emissions (kg capita^{-1} year^{-1})		
Region	**Sub-sector**	Including all territorial emissions (from all stationary combustion, industries, heavy transport etc.)	Removing territorial emissions associated with oil exports (top-down footprint approach of *this study*)	Including only emissions from public energy generation, 'light' vehicles and aviation (similar to N-Calculator footprint approach)
Alberta	Total	45.9	23.0	6.3
	Energy	5.4	5.4	4.9
	Transport	11.4	11.4	1.4
Saskatchewan	Total	39.2	34.0	11.8
	Energy	9.3	9.3	9.0
	Transport	22.5	22.5	2.9
Canada	Total	14.5	11.1	2.7
	Energy	1.8	1.8	1.5
	Transport	7.4	7.4	1.1

In their top-down global input-output study of 188 countries, Oita et al estimated Canada's per capita N footprint to be ~63 kg capita^{-1} year^{-1}, over twice our estimate of 27.1 kg capita^{-1} year^{-1} (Oita et al 2016). The difference in scopes and methodologies of various N footprint studies means that comparisons need to be done carefully, however, valuable insights can still be gained. Oita accounted for a larger range of consumables than in our study, including non-food agricultural products like cotton. We plan to incorporate additional non-food agricultural goods in future assessments of Canada's N footprint, such as textile crops (e.g. hemp and flax), timber products and pet food (e.g. canary seed, of which Canada is the largest exporter in the world (FAOSTAT 2021a)).

3.3.4 N_r reduction policies and future research

Given the relative contribution of meat consumption and transport emissions to all provincial N footprints, moving towards more plant-based diets, and promoting the use of electric vehicles are among policy options that would be relevant across most of the country. Canada has already made strides in this direction by updating Canada's Food Guide in 2019 to encourage Canadians to eat a more plant-based diet (Health Canada 2021c). Furthermore, British Columbia and Quebec have passed legislation to ban the sale of new gas vehicles by 2040 (Canadian Press 2019) and 2035 (Lampert 2020), respectively, and both provinces already provide financial incentives for purchasing electric vehicles. Improving VNFs through better nitrogen use efficiency is also important, particularly for beef, as ammonia emissions from livestock are increasing in Canada (Environment and Climate Change Canada 2021a). Future research studying the change in N footprints over time, in relation to improved N use efficiency in agriculture, changing dietary patterns, and a general movement away from fossil fuels as an energy source, would also be insightful for policy recommendations to lower N emissions. Given the difference in our results between bottom-up and top-down N footprint approaches, additional case studies would be useful to examine how to equitably attribute emissions from transportation, manufacturing, and industrial sectors to a nations' N footprint.

3.4 Conclusions

Here we present the first estimate of Canadian and provincial average N footprints, using a top-down approach. Our results echo the findings of other studies in terms of the large contribution of meat production to N footprints, especially from beef. However, our work also shows variation in the relative importance of drivers of N footprints sub-nationally, particularly in relation to resource extraction. This study gives us a better understanding of the cumulative effect of individual consumption patterns, but also the challenges surrounding the attribution of other economic activities to Canada's N footprint. While uncertainty remains around the fate of N_r released to the Canadian environment as part of these footprints (e.g. N_r recycling from manure and wastewater), estimates of the relative magnitude of N footprint drivers provides a direction for us to begin to reduce them, whether through individual action or through policy intervention. Our study provides novel insights on drivers of N_r emissions at the sub-national scale, emphasizing the need to consider local geographic contexts when examining national N_r emissions.

Data Availability Statement

All data that support the findings of this study, as well as related codes for data preparation and analyses are publicly available on GitHub at: https://github.com/smccou/CAN_N_footprint

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Preface to Chapter 4

Chapter 4 addresses my second research question: How have whole-economy N_r emissions changed over time and what role has economic structure played? As described in Chapter 3, my provincial N footprint model for Canada showed population, meat production and consumption, and fossil fuel combustion were key drivers of total and per capita provincial N_r emissions. Chapter 3 also showed the relative importance of region-specific resource extraction (i.e., the oil and gas industry). However, there are many other potential important drivers of N_r emissions, and my footprint analysis was only for one point in time. Therefore, Chapter 4 expands on these findings and presents a detailed synthesis of multiple forms N_r emissions in Canada over 30 years, including application of decomposition analysis to quantitatively examine drivers. This study provides novel insights into the trends and drivers of whole-economy N_r emissions and underlines the need to consider multiple species of N_r as well as the underlying geographic and policy contexts when studying N_r emissions. My findings show that affluence and population are positive drivers of N_r emissions in Canada, whereas emission intensity (N emissions GDP^{-1}, an aggregate indicator of technology and policy changes) has generally improved. Changes in economic structure have both negative and positive effects on N_r emissions. These results underscore the importance of continued efforts to improve emission intensity, especially in N_r-intensive sectors like oil and gas extraction and agriculture, as well as shifting economies toward less N_r intensive sectors to decouple growth in affluence from N_r pollution.

Chapter 4 was published in *Earth's Future* in September 2022. The format has been modified to be consistent within the thesis. All references cited in Chapter 4 appear at the end of the chapter.

Chapter 4 Decomposing three decades of nitrogen emissions in Canada

Abstract

Reactive nitrogen (N_r) emissions arise from multiple economic sectors, each creating distinct N_r species and impacts on environmental quality. In Canada, the relative contribution of different N_r species to total N_r emissions varies considerably across provinces, yet these N_r species are often studied separately, making comparison difficult. Here, we synthesize data from national emission inventories, as well as agricultural and wastewater statistics, to estimate total and per capita N_r emissions trends across Canada's 10 provinces over three decades between 1990 and 2017. We classified emissions by four main species of N_r, three source sectors, and 13 subsectors. N_r emissions peaked around 2000 followed by reductions both nationally and across almost all provinces. Agriculture replaced fossil fuel combustion as the largest source of N_r emissions after 2008, coinciding with regulatory interventions that aimed to reduce NO_x emissions from transportation, while NH_3 from crop production increased in several provinces. Using an index decomposition analysis, we further assessed the socioeconomic drivers of N_r emissions changes, including the roles of emission intensity (N_r emissions per unit of economic output), affluence, population, and structural changes in the economy. Reduced emission intensity (an aggregate indicator of technology and policy changes) counteracted some of the effects of affluence and population as positive drivers of N_r emissions. Economic structural changes had both large negative and positive effects on N_r emissions. Our results underscore the importance of continued reductions in emissions intensity as well as shifting economies toward less N_r intensive sectors to further decouple affluence from N_r pollution.

Plain Language Summary (requirement of *Earth's Future*)

Human activity releases different forms of reactive nitrogen (any form other than inert nitrogen gas) to the environment in several ways, including fertilizer use and burning fossil fuels. Excess reactive nitrogen contributes to air and water pollution as well as climate change. We therefore examined long-term emission trends of multiple types and sources of reactive nitrogen across Canadian provinces between 1990 and 2017. We investigated what factors were driving changes in emissions, such as population and economic growth, by using an 'index decomposition analysis'. Our results show that, while most reactive nitrogen emissions in the 1990s came from burning fossil fuels, agriculture had become the dominant source of reactive nitrogen by 2017. This change reflects effective policies targeting air pollution from transportation, and an increase in agricultural emissions in some provinces. We found that reactive nitrogen emissions typically increase when wealth and population increase. However, emissions can also be lowered through reduced 'emission intensity': when the economy becomes more efficient in terms of generating output with less nitrogen pollution. The results of our Canadian reactive nitrogen study are important because they demonstrate that careful management and policy attention could further reduce nitrogen pollution alongside continued economic growth.

4.1 Introduction

Multiple species of reactive nitrogen (e.g., NH_3^+, NO_x, NO_3^-, and N_2O) are released by a variety of anthropogenic activities including energy generation, food production, transportation, and wastewater treatment. Excess reactive nitrogen (N_r) results in a range of potential social and environmental costs across spatial and temporal scales (Compton et al 2011; Keeler et al 2016). Due to the 'nitrogen cascade', one molecule of N_r can potentially cause sequential negative impacts including air pollution, eutrophication, and climate change (Galloway et al 2003). Furthermore, actions to reduce one type of N_r may result in an increase in another, simply shifting the environmental burden instead of reducing it. For example, a meta-analysis of field study results by Qiao et al. (2015) found that reducing nitrogen leaching with nitrification inhibitors also decreased nitrous and nitric oxide emissions from agricultural soils but led to elevated ammonia emissions. It is therefore important to assess long-term trends in multiple species of N_r to have a comprehensive understanding of the changes in overall N_r emissions and their potential social and environmental implications.

In many national-scale studies, N_r species are often examined separately (i.e., in relation to air quality, greenhouse gases, or water quality), or are aggregated to total N_r, such as total N_r footprints (e.g., for the United States (Leach et al 2012), Japan (Shibata et al 2014), and Canada (McCourt & MacDonald, 2021)). In Canada, several emission inventories and nitrogen models allow for reporting on separate trends for major N_r species. The Air Pollutant Emissions Inventory (APEI) shows that NO_x emissions are trending downward, while NH_3 emissions are increasing (Environment and Climate Change Canada, 2021a). According to the National Inventory of Greenhouse Gas Emissions, N_2O emissions from agriculture and waste treatment are also increasing (Environment and Climate Change Canada, 2021b). Furthermore, the Residual Soil Nitrogen (RSN) and Indicator Risk of Water Contamination-Nitrogen (IROWC-N) models suggest that NO_3^- leaching from agriculture is increasing (De Jong et al 2009; Drury et al 2007). While national (Clair, 2014) and agricultural (Karimi et al 2020) nitrogen budgets have been published for Canada, to our knowledge, there has been no synthesis of trends in overall N_r emissions nor changes in the relative contributions of different species of N_r.

Beyond quantifying trends in N_r emissions, examining changes in socioeconomic factors associated with the emissions can identify drivers of change (Malik et al 2022). For example, is population growth or changes in consumption a bigger contributor to changes in N_r emissions? Does economic growth itself have a larger impact than relative changes in economic structure, such as shifts in the dominance of different industries? One method to assess drivers behind emissions is decomposition analysis. Decomposition analyses examine the relationship between changes in chosen indicators and aggregate environmental outcomes, such as emissions. Decomposition analyses have been used extensively to evaluate links between economic growth, energy use, greenhouse gas emissions and air pollution (Ang, 2004; de Boer & Rodrigues, 2020). There are two types of decomposition analysis: *structural decomposition* analysis which uses economic input-output tables, and *index decomposition* analysis which uses aggregate economic sector production data. Both approaches allow for assessment of the *production effect* (the effect of changes in total output) and emission intensity effect (the effect of changes in emission per unit of economic output). However, only index decomposition analysis allows for the assessment of economic *structure effect* (the effect of a shift in the production shares of sectors in the economy) (Hoekstra & van den Bergh, 2003).

We are aware of only two published studies that use a decomposition analysis to examine overall national N_r emissions. Wier & Hasler (1999) performed a structural decomposition of national-scale N_r emissions in Denmark, where they identified rising exports and technological change as key factors driving N_r emissions. Malik et al. (2022) also used a structural decomposition to assess the drivers of global N_r emissions, and found that the combined effects of increasing affluence, population growth, and changes in final demand have outpaced any reduction driven by improvements in N_r use efficiency.

Here, we synthesize existing data to examine trends and drivers in N_r emissions nationally across Canada, and sub-nationally for the ten Canadian provinces, over the period 1990 to 2017. This builds on our recent study of Canada's N_r footprint for the circa 2018 period, which showed that total N_r emissions varied substantially across provinces based on the diverse geographic context of this large nation (McCourt and MacDonald, 2021). We examine both aggregate and species-specific N_r emissions from agriculture, industry, transportation, and energy generation. We then perform an index decomposition analysis to determine the primary socioeconomic and technical drivers of N_r emissions, including population growth, affluence, emission intensity, and economic sectoral change. We use emission intensity (N_r emissions per unit of gross domestic product, GDP) as an aggregate indicator for broader changes in technology and policy. Our index decomposition approach allows us to assess the impact of changes in economic structure on N_r emissions, expanding on previous studies that used structural decomposition to examine drivers of N_r emissions for other regions. To our knowledge, this is also the first subnational-level decomposition analysis of N_r emissions. Finally, we briefly discuss the Canadian regulatory policy context that coincides with the temporal trends for specific N_r species and sectors.

4.2 Materials and Methods

4.2.1 An inventory of N_r emissions between 1990 and 2017

We included four major types of N_r in our analysis: 1) NH_3, 2) NO_x, 3) N_2O, and 4) total nitrogen (N) in water (the sum of total Kjeldahl nitrogen [TKN], NO_3^-, and NO_2^-). When aggregating to total N_r emissions, we normalized these as total N per year (Gg N $year^{-1}$) and per capita N per year (kg N $capita^{-1}$ $year^{-1}$). NH_3 and NO_x emissions were obtained from Canada's Air Pollutant Emissions Inventory (Environment and Climate Change Canada, 2021a). N_2O emissions were obtained from Canada's Greenhouse Gas Inventory (Environment and Climate Change Canada, 2021b). To estimate total N_r released to water, we included both N leaching and runoff from agriculture, and N released in effluent after wastewater treatment. For agricultural leaching we multiplied provincial average per hectare leaching rates (kg N ha^{-1}) from the IROWC-N model (De Jong et al 2009) by provincial agricultural areas (ha) from the Census of Agriculture (Agriculture and Agri-Food Canada, 2021). To estimate runoff losses we followed the approach of Karimi et al. (2020), applying 3 kg N ha^{-1} for cropland and 0.94 kg N ha^{-1} for pasture in each year. Agricultural areas from the Census are only available at 5-year intervals, so we held these values constant between reporting years. Average leaching values per hectare from the IROWC-N are provided at 5-year intervals between 1984 and 2006; we therefore held leaching rates per hectare constant after 2006, meaning that inter-annual variability in leaching magnitudes in our study after this date is driven by changes in agricultural areas. Leaching rates per hectare remained relatively constant between 1984 and 2006 except for New Brunswick, Nova Scotia, Prince Edward Island, Quebec, and Newfoundland and Labrador, where they were increasing (see Supporting Information Figure S1). By holding leaching rates constant after 2006 we may therefore underestimate leaching in these provinces, which comprise about ~6% of the agricultural land in Canada.

Available data on total N in wastewater effluent in Canada is sparse (Clair, 2014; Oleszkiewicz & Barnard, 2006). However, data on provincial populations using each wastewater treatment category are available from Environment and Climate Change Canada (2021b). We therefore estimated N_r in effluent from six wastewater treatment categories in each year of our study, which represents wastewater treatment coverage for at least 90% of the Canadian population. We used proxy N effluent values based on annual reports from seven wastewater facilities that include N_r in their effluent reporting (see Table S1). The plants represent four major wastewater treatment technology categories used in Canada: 1) primary settling and filtration treatment (Metro Vancouver, 2017), 2) secondary treatment through activated sludge (Toronto Water, 2018a, 2018b), 3) secondary treatment with biological nutrient removal (City of Kelowna, 2018; EPCOR Water Services Inc., 2019), and 4) trickling filters (Metro Vancouver, 2017). Collectively, these seven facilities directly report on wastewater treatment for 4.5 million Canadians (~12% of the national population in 2017). We additionally used a proxy N_r effluent value for wastewater treatment by lagoons based on several municipal reports (Corporation of the Township of North Glengarry, 2018; Greater Grand Sudbury, 2017, see Table S1). Finally, for septic tank effluent, we used a value of 7 kg N capita^{-1} year $^{-1}$ from the single Canadian study we were able to locate (Brandes 1978), which is of a comparable order of magnitude to the 10 to 25 kg N per household found by the U.S Geological Survey (Seiler, 1996).

4.2.2 Classification of N_r emissions into source sectors

To assess the change in aggregate N_r emissions between different economic sectors, we organized the NH_3, NO_x, N_2O, and total N in water emissions into 3 main source sectors and 13 subsectors. When combined, this results in 33 potential combinations of N_r species by sector and subsector (e.g., *Fossil Fuel Combustion* → *Energy generation* → *NO_x*) (see Table 4-1).

Table 4-1 Categories of N_r species included in the emission synthesis by source sector and subsector. Some minor sector-species combinations were not comprehensively reported across the study period and have been omitted (e.g., biogenic nitric oxide, NO, emission from cropland soils). Note that NO_x and N_2O emissions from agricultural machinery, representing <1% of national N_r emissions in 2017 (Environment and Climate Change Canada, 2021a, Environment and Climate Change Canada, 2021b), are included in the Fossil Fuel → Off-road Transportation subsector following standard Government of Canada reporting.

Sector	Subsector	N_r Species			
		NH_3	**N_2O**	**NO_x**	**Total N in water**
Agriculture	Animal Production	✓	✓		
	Crop Production	✓	✓		
	Runoff and Leaching				✓
Waste and wastewater	Waste Treatment and Incineration	✓	✓	✓	
	Wastewater Effluent				✓
Fossil Fuel Combustion	Energy Generation	✓	✓	✓	
	Oil and Gas Industry	✓	✓	✓	
	Other Industry	✓	✓	✓	
	Road Transportation	✓	✓	✓	
	Off-road Transportation	✓	✓	✓	
	Aviation	✓	✓	✓	
	Marine Transportation	✓	✓	✓	
	Rail Transportation	✓	✓	✓	

4.2.3 Decomposition analysis

To quantify the relative contribution of socioeconomic drivers to changes in N_r emissions, we performed two index decomposition analyses using the additive formulation of logarithmic mean Divisia index (LMDI) method. The LMDI method is widely used to decompose emission changes in environmental studies (e.g., Ang & Zhang, 2000).

4.2.3.1 Technology, affluence, and population decomposition

Building from major emission drivers identified in previous decomposition studies and the Kaya Identity (Štreimikienė & Balezentis, 2016), we aimed to assess three distinct effects: 1) changes in N_r emission intensity (kg N_r emitted per dollar GDP) as an aggregate indicator for improvements in economic efficiency and technology (Su & Ang, 2015), 2) change in affluence through economic growth (GDP per capita) and 3) population growth. We examined the effect of these drivers on total provincial and national N_r emissions, expressed by the following equation:

$$\Delta Nr_t = \Delta(\frac{Nr}{GDP})_t + \Delta(\frac{GDP}{P})_t + \Delta P_t \quad (1)$$

where subscript 't' denotes the time period, ΔNr the change in total N_r emissions for Canada or a province, $\Delta(\frac{Nr}{GDP})$ the change in emission intensity effect, $\Delta(\frac{GDP}{P})$ the change in affluence effect, and ΔP the change in population effect. In addition to the national scale analysis, we selected Alberta, Saskatchewan, and Ontario as representative provinces for decomposition analysis, given that they have the largest total N_r emissions, the highest per capita emissions, and the largest population, respectively.

4.2.3.2 Economic structure and industry-specific decomposition

We further examined drivers by assessing how changes in economic structure have impacted emissions from different industries. We chose two North American Industry Classification System (NAICS) industries as examples for a second set of decomposition analyses: 1) crop and animal production, and 2) the oil and gas industry. These correspond to our three agriculture N_r subsectors and the single oil and gas N_r subsector in Table 4-1. By assessing the drivers for each of these economic sectors individually, we were also able to test if the previous drivers had different impacts—for example, whether technological improvement played distinct roles in crop and animal production as compared to the oil and gas industries.

We selected agriculture and oil and gas N_r emissions for further analysis because these are industries where N_r emissions are still increasing in certain provinces. Not only are these two industries responsible for large amounts of N_r emissions in Canada (Environment and Climate Change Canada, 2021a, 2021b), they are also relatively large drivers of national and provincial GDPs (for example the oil and gas industry created ~20% of Alberta's GDP in 2010; Government of Canada 2021). These sectors also comprise different shares of provincial GDPs and have changed over time. For example, crop and animal production in Saskatchewan contributed 6% of the province's GDP in 2010, which was a decrease from 11% in 2000 (Statistics Canada, 2021b).

By undertaking a provincial-level industry-specific decomposition analysis we therefore aim to examine the geographic and temporal variability in drivers of N_r emissions. The industry-specific decomposition is expressed below (see eq 2). For the two industries, in addition to affluence and population, we assessed the effect of 1) industry N_r emission intensity (industry N_r emissions per industry GDP) and 2) economic structural changes (industry GDP per total GDP).

$$\Delta Nind_t = \Delta(\frac{Nr_{ind}}{GDP_{ind}})_t + \Delta\left(\frac{GDP_{ind}}{GDP}\right)_t + \Delta(\frac{GDP}{P})_t + \Delta P_t \ (2)$$

where subscript ‘t’ denotes the time period, $\Delta Nind$ the change in N_r emissions for a given industry, $\Delta(\frac{Nr_{ind}}{GDP_{ind}})$ the change in industry emission intensity effect, $\Delta\left(\frac{GDP_{ind}}{GDP}\right)$ the change in economic structure effect, $\Delta(\frac{GDP}{P})$ the change in affluence effect, and ΔP the change in population effect. Population and economic data were obtained from Statistics Canada (Statistics Canada, 2021b).

All data processing and analyses were performed with the R statistical programming language v. 4.0.4 (R Core Team, 2021). All datasets and code for this work can be found at Figshare: https://doi.org/10.6084/m9.figshare.19209900.

4.3 Results and discussion

4.3.1 Trends in total and per capita N_r emissions

National total N_r emissions increased by 13% between 1990 and 2000, from 1480 Gg N year^{-1} to 1704 Gg N year^{-1}. They subsequently decreased to 1380 Gg N year^{-1} in 2017 (Figure 4.1a). Per capita emissions ranged from a high of 56 kg N capita^{-1} year^{-1} in 1997 to a low of 38 kg N capita^{-1} year^{-1} in 2017 (Figure 4.1b). Improvements in national per capita emissions (~1% decrease each year between 2012-2017) were mostly offset by increases in population growth (between 2012-2017 Canada had a yearly population growth rate of ~1%; Statistics Canada 2021).

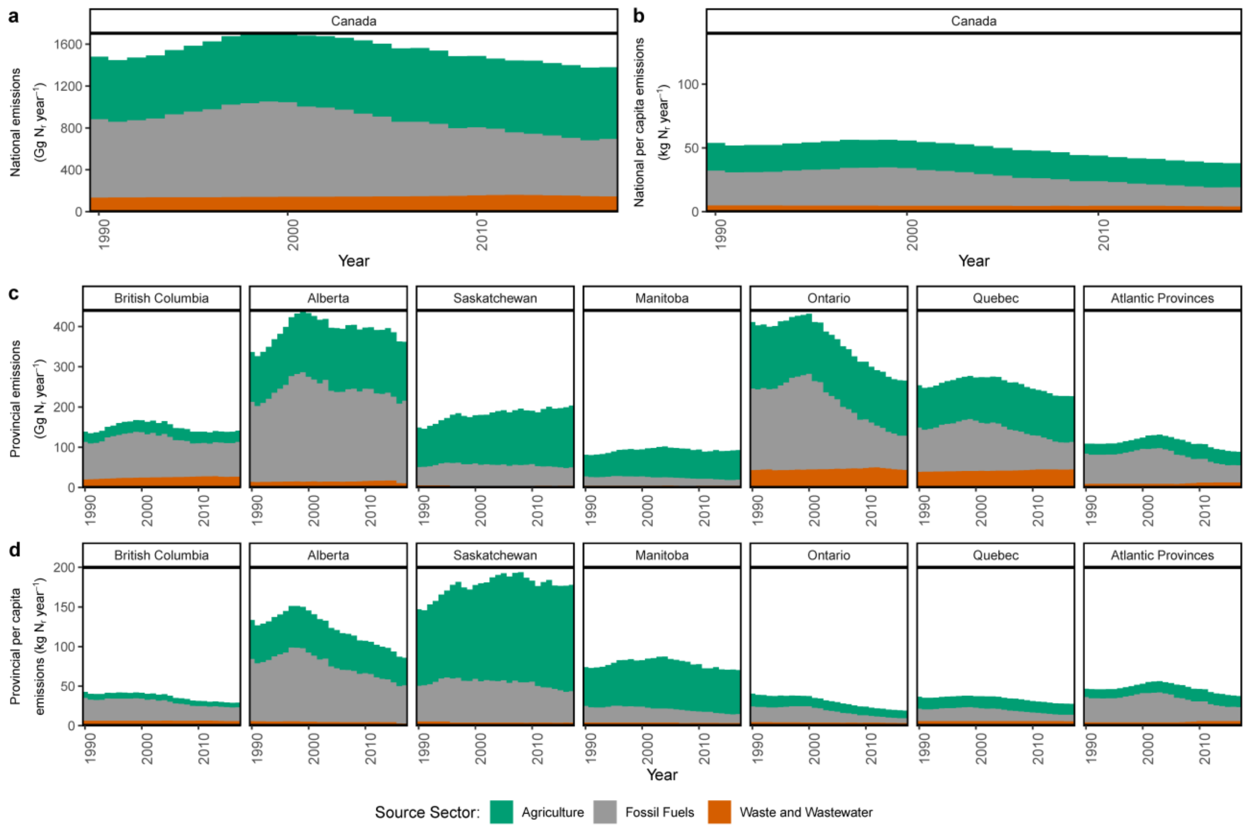

Figure 4.1 Breakdown of total (Gg N year^{-1}) and per capita (kg N capita^{-1} year^{-1}) N_r emissions, nationally (a and b, respectively) and by province (c and d, respectively), between 1990 and 2017. Given their comparatively low individual populations and N_r emissions, the provinces of Prince Edward Island, Nova Scotia, New Brunswick and Newfoundland and Labrador have been aggregated into the 'Atlantic Provinces' panel (see Table S2 for individual values). Provinces are sorted geographically from West to East.

The highest absolute provincial emissions were in Alberta in 1999 and 2000 (440 and 433 Gg N year^{-1} respectively), followed by Ontario (432 Gg N year^{-1} in 2000) (Figure 4.1c). While both provinces had declines in total emissions after the year 2000, sharp reductions in Ontario's N_r emissions contributed disproportionately to the decline in national N_r emissions. Furthermore, when accounting for its large population (nearly 40% of Canada's population resides in Ontario), Ontario had the lowest per capita emissions of any province in 2017 (19 kg N capita $^{-1}$ year^{-1}). Saskatchewan had the highest per capita emissions, both in 2017 (178 kg N capita^{-1} year^{-1}) and in an absolute sense over the study period (194 kg N capita $^{-1}$ year^{-1} in 2008) (Figure 4.1d).

Not only did the quantity of N_r emissions change but the source sector contributions to total N_r emissions also shifted considerably between 1990 and 2017 (Figure 4.1a, b). Fossil fuels contributed more than half of total N_r emissions in Canada for the first half of the study period (1990 to 2003). However, the absolute amount of N_r emissions from fossil fuels, as well as the relative percentage, decreased from a high of 911 Gg N year^{-1} in 1999 (54% of national emissions) to 549 Gg N year^{-1} (40%) in 2017. N_r emissions from agriculture trended in the other direction from 589 Gg N year^{-1} in 1991 (41% of national emissions) to 686 Gg N year^{-1} in 2017 (50%). Therefore, by 2017, agriculture contributed slightly more to national N_r emissions, both in total and relative amounts as compared to fossil fuel combustion. This partly reflects a move towards cleaner sources of fuel in Canada: nearly two thirds of Canada's electrical energy was from hydroelectricity during the study period, and wind and solar power capacity increased 1500% and 700% respectively (Statistics Canada, 2022). It also highlights the need for further efforts and action toward mitigating agricultural Nr emissions in Canada.

The share of N_r from wastewater treatment and waste incineration also increased slightly between 1990 to 2017, from 133 Gg N year^{-1} (9% of national N_r emissions) to 146 Gg N year^{-1} (11%), respectively (Figure 4.1a). Trends in waste-related N_r largely follow population across provinces and over time. Ontario had the highest total N_r from waste and wastewater treatment (50 Gg N in 2012, 17% of its total provincial emissions). Coastal provinces also tend to have lower wastewater treatment levels and higher per capita wastewater N_r than landlocked inland provinces. For example, in 2017, the Atlantic provinces, Quebec and British Columbia had the highest per capita N_r emissions from wastewater (all at ~5 kg N capita^{-1} year^{-1}). In contrast, Alberta had higher wastewater treatment levels and the lowest per capita N_r emissions from wastewater (2 kg N capita^{-1} year^{-1}) (Figure 4.1d), likely reflecting that its two major population centers are located on rivers and its largest city (Calgary) is in a semi-arid, prairie climate with less capacity to dilute aqueous N_r pollution.

4.3.2 The role of regulatory policy in decreasing fossil fuel N_r emissions

Reductions in fossil fuel related N_r emissions, primarily as NO_x, have contributed the most to overall N_r emissions trends nationally. While NO_x emissions have decreased across all provinces, the rate of decrease varies. Ontario had the largest absolute and percentage decrease in total and per capita NO_x emissions, from 222 to 79 Gg N year^{-1}, and 19 to 6 kg N capita^{-1} year^{-1} (a 64% and 68% decrease respectively between 2000 and 2017). By comparison, Alberta's total NO_x emissions have decreased from 261 to 194 Gg N year^{-1}, and per capita NO_x emissions have decreased from 90 to 45 kg N capita^{-1} year^{-1} (a 26% and 50% decrease, respectively) (Figure 4.1, Figure 4.2).

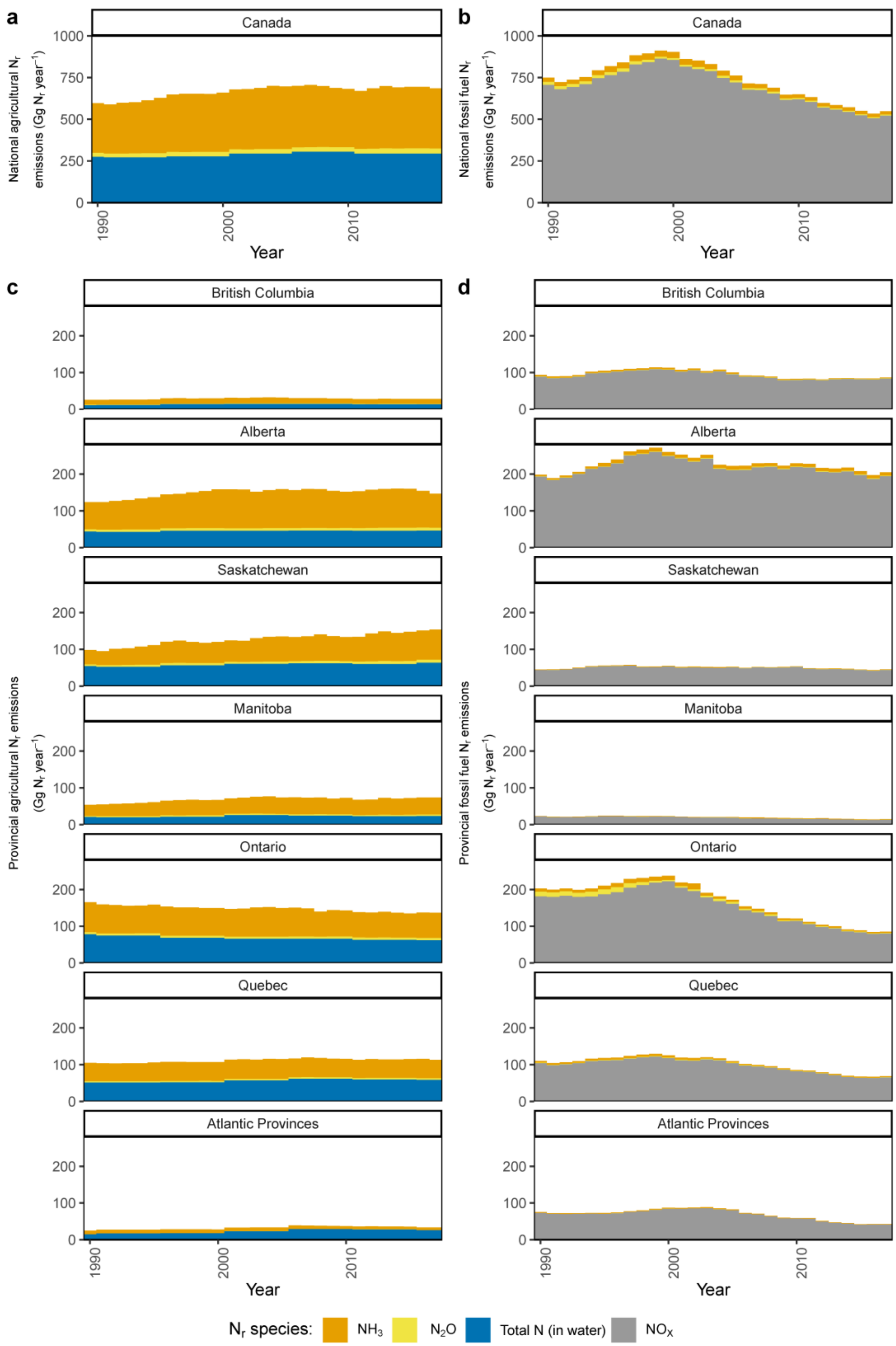

Figure 4.2 Summary and comparison of Nr species from agricultural sources (left side) with those from fossil fuel combustion (right side) nationally (a, b) and for each province (c, d) from 1990 to 2017. The dominant source of emissions nationally shifted from fossil fuels to agriculture around the year 2008. Provinces are sorted geographically from West to East.

Road transportation and the oil and gas industry were the two subsectors that contributed most to fossil fuel N_r (24% and 27% of national fuel combustion emissions in 2017, respectively), and therefore NO_x emissions (Figure 4.3). Improvements in road transport emissions led to the greatest reductions in NO_x emissions. NO_x from road transport peaked in 2000 (287 Gg N $year^{-1}$ or 17% of total national N_r emissions) and decreased to 122 Gg N $year^{-1}$ (~10%) by 2017. NO_x emissions from oil and gas follow a similar trend, peaking around 2000 (at 156 Gg N $year^{-1}$ nationally) and then decreasing. Oil-related NO_x emissions are geographically concentrated in one province, Alberta, where most of Canada's oil and gas industry is located. In 2017, the oil industry in Alberta emitted 114 Gg N, representing more than three-quarters of Canada's oil-related N_r emissions that year.

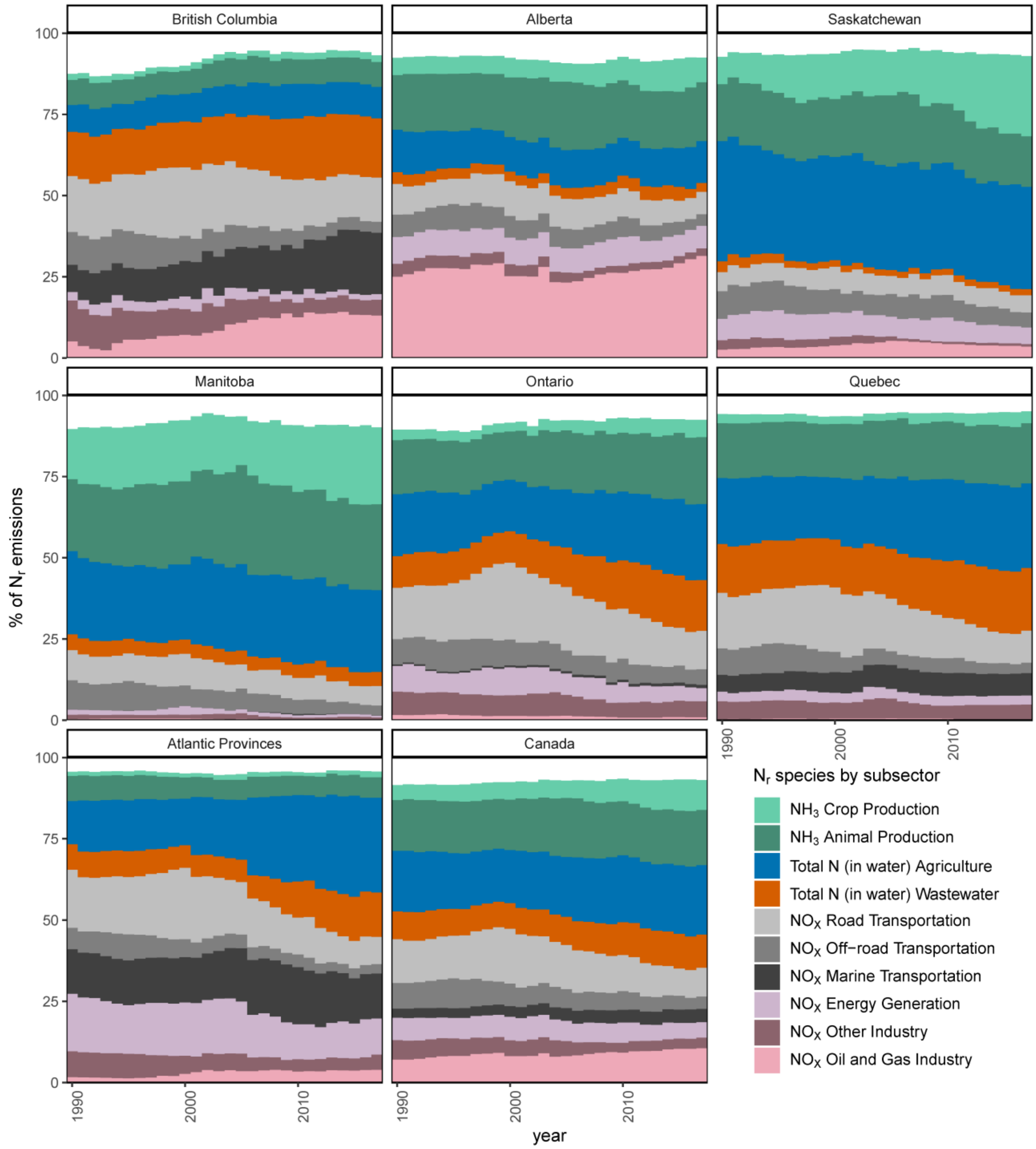

Figure 4.3 Classification of relative subsector and N_r species contributions as a percentage of total N_r emissions in each province and nationally between 1990 and 2017. Only those categories that were in the top five emission sources in any year across all provinces are included to allow for easier visual interpretation, which omits N_2O. The 10 included categories (out of the possible 33 categories shown in Table 1) cover at least 87% of all N_r emissions in each province throughout the study period. The legend is sorted from top-bottom for three species: ammonia (NH_3), total N in water, and nitrogen oxides (NO_x).

Reductions in NO_x emissions coincide with changes in government policy that aimed to reduce them. In the late 1980s and early 1990s, Canada signed and ratified several international agreements to reduce NO_x emissions, including the Sofia Protocol of the UNECE Convention on Long-Range Transboundary Air Pollution in 1988 and the Canada-US Air Quality Agreement in 1991. These agreements focused on implementing increasingly stringent national vehicle standards and reducing NO_x emissions from industry with a national NO_x emissions cap of 2250 Gg year^{-1} by 2010, and Canada met its proposed targets (Environment and Climate Change Canada, 2020b). In 2017, Canada ratified the Gothenburg Protocol, which replaced the Sofia Protocol and addresses pollutants that cause acidification and ground-level ozone (including NO_x). Under this protocol Canada committed to reduce NO_x emissions by 35% from 2005 levels by 2020 (Environment and Climate Change Canada, 2020).

4.3.3 Shifting agricultural N_r emissions and policy gaps

By 2017, agriculture was the largest source of N_r emissions in Canada, although this was partly attributable to success in reducing fossil fuel N_r. Agricultural emissions at the national scale have been comparatively stable, ranging from 597 Gg N year^{-1} in 1990 to a high of 705 Gg N year^{-1} in 2007, with a slight decline to 686 Gg N year^{-1} in 2017 (Figure 4.2). However, provincial-level trends in agricultural N_r emissions have been redistributed across and between provinces. For example, in Ontario, the province with the largest annual agricultural emissions, these decreased by 16%, from 1655 Gg N year^{-1} in 1990 to 137 Gg N year^{-1} in 2017. Nationally, such reductions were offset by growth in agricultural N_r emissions in other provinces, especially Saskatchewan, where these increased by 60% from 95 to 153 Gg N year^{-1} between 1990 and 2017 (Figure 4.2).

Nationally, agricultural N_r emissions are primarily (~50% across all years of our study) in the form of NH_3 from crop production (e.g., synthetic fertilizer use) and animal production (e.g., from manure management). This is also true across most provinces, although in Quebec and the Atlantic provinces, runoff and leaching are a relatively larger source of N_r in some years (Figure 4.3). Across most provinces and most years, the main source of NH_3 emissions was animal production (except in Saskatchewan between 2012-2017 where NH_3 from crop production accounted for ~30% of agricultural N_r emissions). In fact, as a percentage of overall N_r emissions nationally, NH_3 emissions from animal production surpassed those of NO_x emissions from road transportation during the study period except for 1999 and 2000 (Figure 4.3).

Most provinces have passed regulations related to agricultural nutrient management aimed at reducing N_r losses to the environment. Examples include Ontario's Nutrient Management Act (2002) and Alberta's Agricultural Operation Practices Act (2000). Current legislation generally focuses on reducing greenhouse gas emissions and limiting N_r loading to water bodies through farm nutrient management plans, including through the timing of fertilizer and manure applications as well as maintaining vegetative buffer strips to protect water bodies. However, unlike NO_x emissions, NH_3 is not as stringently regulated in Canada. While the Gothenburg Protocol in theory also covers some NH_3 emissions by regulating ammonium (NH_4) and several provinces have air quality targets that include NH_3 (for example, Alberta Environment, 2005; Manitoba Environment, Climate and Parks, 2005), Canada currently has no national reduction goals in place for NH_3 (Environment and Climate Change Canada, 2020b). NH_3 emissions can lead to acidification and potential human health hazards through $PM_{2.5}$ formation (Gu et al 2021). Efforts to reduce NH_3 emissions therefore warrant additional policy attention in Canada given that these emissions have been increasing.

4.3.4 Technology and efficiency improvements can offset positive drivers of growth in total N_r emissions

Reductions in total N_r emissions were driven predominantly by reductions in N_r emission intensity (Gg N GDP^{-1}), which we use as an indicator for broader technological and policy changes. The reduction in emission intensity effect was particularly strong between 2000 and 2010, during which the greatest reduction in N_r emissions occurred nationally (-217 Gg N) and across Alberta and Ontario (Table 2). Figure 4.4 shows the detailed changes in each of the three drivers subnationally across Canada over the study period. Emission intensity peaks around 2000 for most provinces and then decreases in all provinces, except in Saskatchewan (Figure 4.4a). This improvement in N_r efficiency occurred most strongly in the decade after the Gothenburg Protocol was ratified, suggesting that the greatest gains in efficiency happened fairly quickly and have since tapered off.

However, reductions in emission intensity were not always strong enough to outweigh the positive drivers of affluence and population. Increased affluence (GDP $capita^{-1}$) was the dominant positive driver in overall N_r emissions changes over time (except Alberta between 2010-2017), especially between 1990 and 2000 nationally, and in Alberta and Ontario (accounting for +608 Gg N, +192 Gg N and +152 Gg N, respectively) (Table 4-2). Combined with the additional positive effect of population growth, these positive pressures resulted in net N_r emission growth during the 1990s across Canada and the three example provinces. In Alberta, population growth was the dominant positive pressure between 2010-2017 (+50 Gg N). Between 2010 and 2017 Alberta's population grew by 12% (Figure 4.4), which was the largest percentage increase of any province during this time (Statistics Canada, 2021a).

Table 4-2 Decomposition of changes in overall N_r emissions between 1990 and 2017 across Canada and the provinces of Alberta, Saskatchewan, and Ontario. Drivers assessed are: 1) N_r emission intensity (Gg N_r GDP^{-1}), 2) affluence (GDP $capita^{-1}$), and 3) population. Our analysis is divided into three decades to examine differences in drivers between 1990 and 2000, where N_r emissions generally increased, and the following decades, where there was a decrease in N_r emissions across all provinces except Saskatchewan. The change in total N_r emissions is equal to the sum of the positive or negative pressures across the three drivers for that decade. The effect with the largest absolute value (positive or negative) for each area and decade is ***bolded*** *and listed as the main driver of N_r emissions. In years where there is less than a 10% difference in absolute magnitude, we indicate (with '+/-') that the largest positive and negative drivers effectively cancel each other out, and both drivers are bolded.*

Area	Years	N_r emission change (Δ Gg N)	Emission intensity (EI) effect (Δ Gg N)	Affluence effect (Δ Gg N)	Population effect (Δ Gg N)	Main driver
Canada	1990-2000	+225	-552	**+608**	+168	+Affluence
	2000-2010	-217	**-880**	+500	+163	-EI
	2010-2017	-107	**-459**	+249	+102	-EI
Alberta	1990-2000	+97	-158	**+192**	+63	+Affluence
	2000-2010	-36	**-293**	+166	+91	-EI
	2010-2017	-35	**-111**	+26	+50	-EI
Ontario	1990-2000	+21	**-185**	+152	+54	-EI
	2000-2010	-119	**-245**	+81	+44	-EI
	2010-2017	-47	**-123**	+56	+20	-EI
Saskatchewan	1990-2000	+31	-35	**+66**	0	+Affluence
	2000-2010	+11	**-104**	**+110**	+6	+/-
	2010-2017	+13	**-32**	+27	+18	-EI

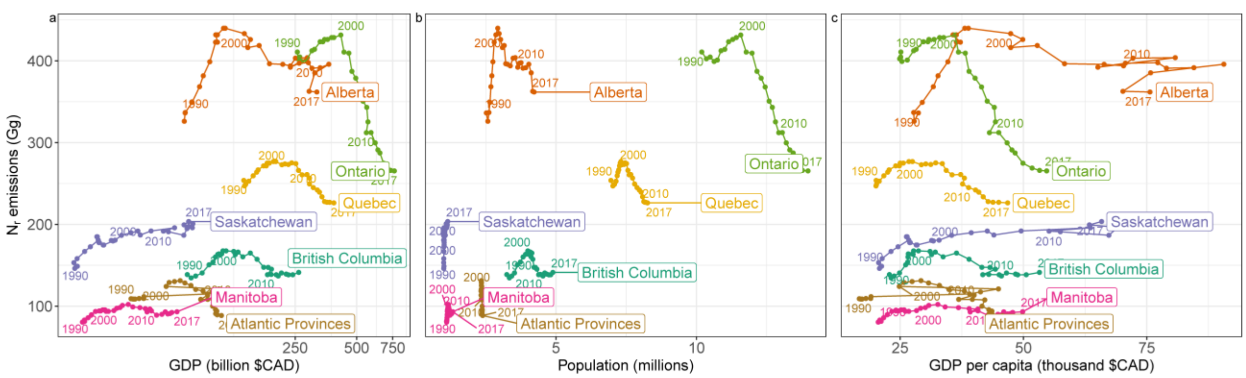

Figure 4.4 Changes in provincial N_r emissions compared to changes in (a) GDP (in billion \$CAD, current dollars), (b) population, and (c) GDP per capita (thousand \$CAD) between 1990-2017. Note the logarithmic scale for the x axis in (a). The data in panel (a) represents how the emission intensity indicator was derived in our study (N_r emitted per unit GDP).

4.3.5 Sectoral N_r emissions and the influence of economic structural changes

When examining N_r emissions by economic sector, the emission intensity effect is also no longer always a negative driver (as it was when looking at the whole economy in Table 4-2). For example, during 2010-2017 change in emission intensity was a positive driver of oil and gas N_r emissions in Alberta (Table 4-3), meaning that emission intensity of oil production increased over these years. One potential explanation for the increased emission intensity is the fact that as the price of oil rises, "dirtier" and less easily accessible oil becomes more economically viable and producing oil from unconventional reservoirs results in more emissions intensive production (Canadian Association of Petroleum Producers, 2012). On the other hand, the emission-reducing effect of decreased agricultural emissions intensity generally expanded over the study period (Table 4-3), coinciding with improvements in N_r-use efficiency in some provinces (Karimi et al 2020).

Table 4-3 Decomposition of sectoral changes in N_r emissions from two NAICS economic sectors, agriculture and oil & gas, between 1990 and 2017 across Canada and the provinces of Alberta, Saskatchewan, and Ontario. Drivers assessed are: 1) Sectoral N_r emissions intensity (Gg N_r sectoral GDP^{-1}), 2) economic structural change (sectoral GDP GDP^{-1}), 3) affluence (GDP $capita^{-1}$), and 4) population. The change in sectoral N emissions is equal to the sum of the effects of the chosen drivers for that decade (the totals may differ slightly due to rounding). The single largest positive or negative effect for each sector in each period is ***bolded*** *and interpreted as having the largest impact on the overall N emission change magnitude and direction for each sector. In some years, there are multiple roughly equivalent (within 10% difference in absolute magnitude) drivers; when there are two of these, both drivers are bolded, otherwise if there are several, none are bolded. The ES effect was largest absolute value in multiple cases.*

Area	Years	Agricultural industry (three agriculture N_r subsectors)					Oil & Gas industry (single N_r subsector)				
		Emission change (Δ Gg N)	**ES effect**	EI effect	AF effect	Pop. Effect	Emission change (Δ Gg N)	**ES effect**	EI effect	AF effect	Pop. Effect
CA	1990-2000	+63	-165	-79	**+240**	+66	+36	+66	**-84**	+41	+13
	2000-2010	+22	-170	-86	**+210**	+69	-2	+36	**-96**	+44	+14
	2010-2017	+4	+190	**-354**	+119	+49	+10	**-60**	+35	+25	+10
AB	1990-2000	+35	**-116**	+57	+71	+23	+26	+26	**-59**	+44	+16
	2000-2010	-7	-50	-52	**+62**	+34	-5	-1	**-72**	+43	+24
	2010-2017	-5	+99	**-134**	+10	+20	+10	**-36**	+24	+8	+15
ON	1990-2000	-16	**-120**	+27	+57	+20	-1	-2	-2	+2	+1
	2000-2010	-7	+45	**-102**	+32	+18	-3	+3	**-7**	+1	0
	2010-2017	-6	+17	**-60**	+27	+9	0	+1	0	0	0
SK	1990-2000	+22	**-91**	+69	+44	0	+3	+3	-2	+2	0
	2000-2010	+13	-19	-47	**+75**	+4	+1	+2	**-6**	**+5**	0
	2010-2017	+21	+86	**-98**	+19	+13	-1	**-4**	+1	+1	+1

Abbreviations: CA: Canada, AB: Alberta, ON, Ontario, SK: Saskatchewan, EI: emission intensity, ES: economic structure, AF: affluence.

Affluence remained a relatively stronger positive pressure on N_r emissions than population for both agriculture (e.g., in Ontario between 1990 and 2000) and oil and gas (e.g., Alberta between 1990 and 2000) (Table 4-3). However, our sectoral analysis shows the important but variable roles of economic structure and emission intensity as drivers of changes in sectoral N_r emissions. For example, the increase in the agricultural sector's contribution to provincial GDP was the largest positive pressure on increased N_r emissions in Saskatchewan from 2010 to 2017 (although this was effectively cancelled out by a negative emission intensity effect), whereas change in economic structure was the largest negative pressure behind the reduction in agricultural emissions in Ontario between 1990 and 2000. Ontario is the sole province where the N_r emission-reducing effect of changes in agricultural emissions intensity and economic structure was enough to outweigh positive pressure from affluence and population growth consistently across all time periods. Ontario shows by far the sharpest reduction in overall N_r emission intensity (Figure 4.4a).

Our results are similar to those of Malik et al. (2022), who performed a structural decomposition analysis of changes in global N_r emissions. They showed that the combined effect of affluence, population growth, and changes in final demand (particularly resulting from economic effects of trade) outweighed any negative pressure from improved N_r efficiency resulting in growth in global N_r emissions, especially from agriculture. Considering that several Canadian provinces are actively encouraging growth in the agricultural sector, with an emphasis on growing export markets for agricultural goods (e.g. Saskatchewan Ministry of Agriculture (2022)), additional policy focus needs to be put on further reducing emission intensity to ensure sustainable growth in the agricultural sector.

4.3.6 Uncertainties and limitations

Index decomposition analysis is a useful method to quantify the impact of different drivers on emissions, but it has limitations. Our choice of drivers and interpretation was informed by previous studies: for example, Kastner et al. (2012) and Malik et al. (2022) use relatively simple indicators of 'technology' change in their global decomposition analysis studies (i.e., crop yields and nitrogen efficiency, respectively), and we selected N_r emission intensity for this purpose given that emission intensity has been widely used as an aggregate indicator of policy control (Thomakos & Alexopoulos, 2016). However, while emission intensity provides context to changes in N_r emissions over time, it does not precisely capture the effects of either technology or policy. We therefore cannot separate the success of specific policies from other effects, such as behavioural changes or improvements in technological efficiency (Goh, 2019). Furthermore, while the N_r emissions categories from government inventories and the economic sectors from the NAICS used in our study broadly match each other, there is not a perfect pairing, which could affect our results (see Table S3 for a comparison). Our analysis also only addresses sector-wide changes and does not address changes occurring below the level of aggregation available in our data (e.g., shifts between more or less nitrogen-intensive crops).

Our analysis contains multiple forms of uncertainty. Uncertainties around the NH_3, N_2O and NO_x values used in our study are described in the corresponding government inventories. For example, Canada's Greenhouse Gas Inventory notes considerable uncertainty (at least ±30%) around mean values for N_2O emissions from manure management and agricultural soils (Environment and Climate Change Canada, 2021b). Canada's Air Pollutant Emissions Inventory similarly mentions that some emission categories related to NH_3 and NO_x are calculated with "in-house" estimates using relatively basic (Tier 1) methodologies that rely on activity data and emission factors (Environment and Climate Change 2021a). We use further basic assumptions around total N in water from runoff, leaching, and wastewater effluent given limited data availability. At the national scale, our results for those variables broadly compare to a national N_r budget study by Clair et al. (2014): our results for the year 2007 are slightly higher for runoff and leaching (306 Gg N in our study vs. 274 Gg N by Clair et al., 2014) and for wastewater (141 Gg N vs. 137 Gg N, respectively). Our agricultural runoff and leaching estimates are therefore particularly uncertain, in part because we do not capture differences in runoff across Canada's diverse hydroclimatic regions and cropping systems. However, our results for runoff and leaching are within 2-3% of those reported by Karimi et al. (2020) nationally for 1996 and 2016.

4.4 Conclusions

In this paper, we present the first synthesis and decomposition analysis of Canadian N_r emission trends. By classifying emissions into a set of 33 subsectors by N_r species combinations subnationally across Canadian provinces, our results show a detailed view of the contributors to N_r pollution from different economic activity sources, and how these have varied both geographically and temporally. Substantial reductions have been achieved in fossil fuel related N_r emissions, especially NO_x from road transportation. Consequently, agriculture is now a slightly larger overall source of N_r emissions, primarily in the form of NH_3. While agricultural N_r emissions have been relatively stable at the national scale, the share of N_r species from agriculture has grown in several provinces, including Saskatchewan, Ontario, and the Atlantic Provinces. Further policy attention to the more diffuse agricultural sources of N_r pollution in the Canadian context is needed, although effectiveness of regulatory policy mechanisms may be more difficult to achieve than in the case of NO_x, stressing the need for innovative approaches.

Our decomposition analysis results for Canada are in line with findings of other studies showing that growing population and affluence are positive drivers of N_r emissions. However, these effects have been increasingly offset by reductions in emission intensity. Our study also highlights the importance of changes in economic structure in driving N_r emissions, which may play a key role in achieving future N_r emissions reductions in Canada. Our study provides novel insights into the trends and drivers of N_r emissions provincially, underlining the need to consider multiple species of N_r as well as the underlying geographic and policy contexts when studying N_r emissions. Additional political and scientific attention should be given to examining how we might diversify our economies away from N_r intensive sectors, further reduce emission intensity, and decouple affluence from N_r pollution.

Acknowledgments

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Open Research and Data Availability Statement

The R scripts and data used to execute the analyses in this paper are preserved at Figshare (McCourt, 2022), under CC BY 4.0 license.

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Preface to Chapter 5

Chapter 5 addresses my research question: What opportunities do nutrient-related legislation provide to support innovative nutrient policy integration? In Chapters 3 and 4 I showed the diversity of economic sources and sectors involved in creating anthropogenic N_r emissions in Canada. I also show in Chapter 4 that changes in N_r emissions often coincide with regulatory interventions (e.g., reductions in NO_x emissions following policies aimed to reduce air pollution from transportation), and that diffuse sources of N_r in Canada (like NH_3 from agriculture) are still increasing. As I discussed in my literature review, we need innovative N_r policies, and nutrient policies in general, to better address nutrient pollution. However, scientists and policymakers have a limited understanding about the breadth and scope of existing nutrient policies, which impedes our ability to identify areas for nutrient policy integration.

In Chapter 5 I propose the application of a new technique to identify possible entry points for better nutrient integration across provincial and federal law in Canada. I use semantic network analysis to create a network of legislative texts that are connected by common terms. Through this analysis I identify common topics in Canadian legislation, including “policy hubs” and “policy bridges”—laws that are highly connected or create unique links in the overall network structure. These hub and bridge laws are particularly interesting examples of existing policy integration or those with high potential for new integration. In this chapter I also discuss the importance of ‘indirect’ legislative topics for nutrient for nutrient policy integration (such as food marketing regulations).

This chapter will be submitted to a journal in late November 2022. It has been formatted according to requirements for the journal Nature Sustainability. All references cited in Chapter 5 appear at the end of the chapter.

Chapter 5 Identifying leverage points for sustainable nutrient policy integration in Canada

Abstract

Mitigating nutrient pollution requires policies spanning across diverse economic sectors and environmental systems. We therefore propose a novel methodology, applying semantic network analysis for linking policy texts through shared terms, to detect common topics and connections as entry points for nutrient policy integration. Using nutrient-related law in Canada, our analysis shows twelve topics with issues spanning from agricultural management to climate change. Topics such as food marketing indirectly relate to nutrient management, revealing potential for new nutrient policy integration. Several environmental protection and land use planning laws are highly connected in the network, serving as examples of possible "policy hubs" by connecting multiple other economic and environmental statutes. Other legislation, representing "policy bridges", creates unique links in the overall network structure, potentially improving integration across the Canadian policy landscape. Assessing existing legislative texts as a network reveals opportunities to improve policy integration and enhance our ability to mitigate nutrient pollution.

5.1 Introduction

Sustainable management of nutrients, such as nitrogen (N) and phosphorus (P), plays a crucial role in food production, climate change, human health, biodiversity, and air and water quality(Lade et al., 2020). Yet, reducing nutrient pollution is well understood to be a ‘wicked problem’, involving competing goals of producing more food while protecting the environment, and a multitude of actors and economic pressures influencing an increasingly globalized food supply chain[2,3]. The policy landscape around N and P management is similarly complex[4,5]. There are potential co-benefits found in joint nutrient strategies, as both N and P pollution mainly derive from the same agricultural sources, and measures to reduces losses of one nutrient can also reduce losses of the other. However, it is equally important to acknowledge that there are key differences in N and P cycles (e.g. fossil fuel combustion contributes to N pollution and impacts air quality and greenhouse gas emissions, while P does not)[6-8].

New and innovative policies are needed to address nutrient pollution, especially from diffuse agricultural sources[9]. National policies have a key role to play in encouraging better nutrient management, but often do not reflect the multitude of economic sectors, sources, and environmental and health impacts involved in nutrient management[6,10]. Inventorying existing policies and assessing potential nutrient policy integration (incorporating goals into policy sectors not focused on nutrient management[11]) is therefore a crucial step in addressing underlying drivers of nutrient pollution, achieving multiple nutrient management objectives simultaneously, reducing policy transaction costs, and increasing the likelihood that governments’ nutrient goals are met[5,12]. Such analysis is needed to help governments design better policies by identifying leverage points for enhanced policy integration.

Semantic network analysis is well suited to identify areas for novel policy integration by detecting connections between existing nutrient-related policies and 'communities' of policies that refer to similar topics. This approach creates a network where nodes (nutrient policy texts) are linked by edges (common words shared between texts)[13]. Network analysis could be useful for examining complex interconnected policy environments because it also allows for identification of 'bridges' that are creating unique connections in the network, and 'hubs' that are particularly strongly connected within the policy network[14,15]. Semantic networks have been used extensively in research across multiple disciplines, especially in analysis of political discourse, and social media[16,17]. Previous work has applied semantic network analysis to examine trends in national environmental policy links in Korea[18] and to assess interactions between the Sustainable Development Goals (SDG's) in official United Nations documents globally[19,20]; however, to our knowledge, it has not yet been applied to examine networks of nutrient policies (but see Alshtröm and Cornell's analysis of the structural properties of governance of global N and P cycle[21]).

Our analysis builds on previous nutrient policy studies to develop a more comprehensive understanding of how existing N and P management strategies are interconnected and to identify potential new areas for nutrient policy integration. We do so by applying a semantic network analysis with natural language processing to nutrient-related legislation in Canada which was identified through a database search. Canada offers an informative case study to examine the breadth and depth of nutrient policy integration more generally. For example, there have been attempts in Canada to create nutrient-focused legislation that directly addresses nutrient management (e.g., the Nutrient Management Act passed in Ontario in 2002). Our objective was to define the Canadian nutrient-related legislation landscape as a network that embodies a holistic approach to examining N and P policies. Our findings reveal different types of policies that are particularly impactful in the network structure, representing opportunities to examine both existing policy integration and the development of more comprehensive policies. This is important because a 'siloed' approach to addressing nutrient pollution can exacerbate or create new problems, such as pollution swapping[6].

5.2 Results and Discussion

We identified 245 nutrient-related Acts (written laws, sometimes referred to as statutes, which are enacted by federal or provincial parliaments and are currently in force across Canada or in one of the 10 Canadian provinces) that form 12 different topic clusters in the semantic network. Figure 5.1 shows the connections between individual Acts (Figure 5.1a) and topic groups (Figure 5.1b), and Table 5-1 displays the shared words that resulted in Acts being clustered together into each topic. Many topics contain Acts that indirectly relate to nutrient management (e.g., land use and planning) highlighting areas for potential new policy integration around nutrient management. Some Acts serve as "policy hubs" due to their high connectivity in the network (e.g., the Environment Act in Ontario), while others represent potential "policy bridges" by creating unique links across topics (e.g., the Nutrient Management Act in Ontario) (Figure 5.1a). Both of these types of cross-cutting legislation may be key opportunities for more innovative and comprehensive policies around nutrients, as 'hub' Acts indicate central texts in the network that have multiple connections representing frequently referenced core issues[15] and 'bridge' Acts may be platforms for creating novel nutrient legislation ideas[14,17].

5.2.1 Nutrient legislation topic classification.

The 12 topics identified through the network clustering analysis cover a wide range of subjects ranging from environmental concerns to a focus on specific economic sectors. We named the topics (shown in *italics* throughout the text) based on the titles of Acts included in the topic, Act preambles, and the top common words derived from the network clustering analysis (see Table 5-1).

Four of the 12 topics contain legislation that focuses on mitigating negative outcomes to society and the environment. These range from *environmental quality* Acts (broad pieces of legislation that cover a variety of concerns including protecting soil, air, and water quality), to laws focused on abating c*limate change*, protecting *animal and public health*, or ensuring *occupational health and safety*. Four groups concentrate on economic sectors, namely the *forestry* sector, the *oil, gas and mining* sector, as well as two related to agriculture: *agricultural management* and *food marketing and regulations*. The prominence of natural resource-related topics reflects the importance of these areas to the Canadian economy[22]. Acts in the *fisheries and biodiversity* topic deal both with biodiversity protection, often in relation to fish habitat, and the fishery sector. One topic included Acts that focus on regulatory mechanisms relating to *vehicles,* including fuel taxes and retail sales taxes, generally with the aim to reduce carbon emissions and protect air quality. Finally, two topics are focused on legislation relating to land use and government jurisdictional organizational structure: *land use and planning* and *land conservation*.

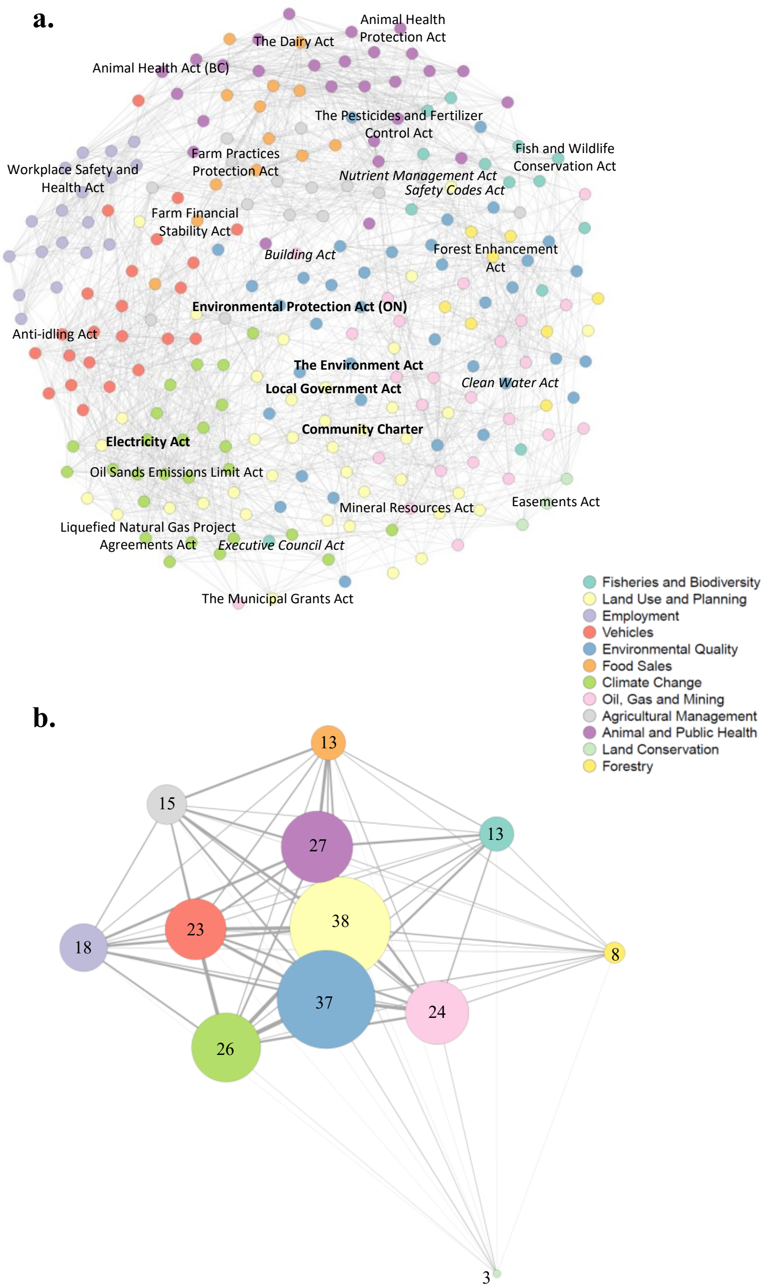

Figure 5.1 The network of nutrient-related Acts across Canada. The colors of the nodes represent groups of Acts identified with the Leiden clustering method using a resolution of 1.35. In graph a. each node represents an Act, and the edges represent common words shared between them (edges have been trimmed for visual clarity). Several nodes have been labelled to show representative examples of Acts in each group: those titles that are in bold are the top 5 hub Acts, meaning that they have the shortest distance to reach every other node in the network, while titles that are italicized are the top 5 bridge acts which have the fewest redundant shared neighbors and act as unique links in the network (see Table 5-2 and Methods for more detail). Graph b. is a contracted network that simplifies the connections between the same group of Acts from a. The size of the nodes represents the number of Acts in the topic group, and the edge thickness represents the weight of the combined edges between Acts in two groups.

Table 5-1. List of topics identified by a Leiden clustering analysis of Canadian nutrient-related legislation (using a clustering resolution of 1.35). The top 10 terms with the highest TFIDF weight (see Methods) occurring within each group are shown. Topic names were chosen based on the common terms, as well as the titles of Acts in each topic (see Supplementary Material for full list of Acts and topic groups).

Topic name	Top 10 terms appearing in each topic
Fisheries and Biodiversity	aquaculture, fish, species, fishery, wildlife, bear, licence, fishing, gear, carton
Land Use and Planning	municipality, irrigation, district, marshland, company, taxpayer, taxation, foundation, land, election
Occupational Health and Safety	worker, employer, workplace, apprenticeship, trade, committee, health, accident, earning, apprentice
Vehicles	fuel, motor, vehicle, deplete, passenger, collector, vendor, driver, supplier, engine
Environmental Quality	water, basin, project, contaminant, proponent, waste, environment, wetland, vessel, cross
Food Marketing and Regulations	dairy, milk, producer, marketing, product, processor, inspector, commodity, farm, quota
Climate Change	emission, greenhouse, climate, energy, target, electricity, generator, efficiency, goal, carbon
Oil, Gas and Mining	regulator, mineral, rice, licence, perpetuity, royalty, mining, coal, recorder, licensee
Agricultural Management	farm, crop, practice, farmer, disturbance, board, nuisance, insurance, dust, smoke
Animal and Public Health	animal, inspector, disease, health, fertilizer, livestock, food, chief, veterinarian, licence
Land Conservation	easement, conservation, covenant, pleading, land, profit, titles, claim, escarpment, watercourse
Forestry	forest, timber, tree, forestry, land, quota, forests, commissioner, licence, range

5.2.2 Cross-cutting ‘hub’ and ‘bridge’ legislation

In addition to detecting topic clusters, our semantic network analysis identifies “hub” policies that are strongly connected to all other policies in the network, and “bridge” policies that create unique links in the network. These statutes may offer important opportunities for nutrient policy integration within the existing landscape of Canadian nutrient policy. Table 5-2 shows the top five hub Acts, as measured by their ‘closeness’ centrality score, and bridge Acts, as measured by their Burt’s Constraint score (see Methods section for additional detail).

Table 5-2 Top five hub and bridge acts in the Canadian nutrient network as measured by their closeness and Burt's constraint scores respectively (see Methods section for additional detail).

Centrality Measure	Rank	Act Title	Corresponding Topic	Top 3 Topic Connections
Closeness (Hub Acts)	1	Environmental Protection Act (Ontario)	Environmental Quality	Environmental quality, land use and planning, climate change
	2	Local Government Act (British Columbia)	Land Use and Planning	Land use and planning, environmental quality, climate change
	3	The Environment Act (Manitoba)	Environmental Quality	Environmental quality, land use and planning, climate change
	4	Electricity Act, 1998 (Ontario)	Climate Change	Climate change, land use and planning, vehicles
	5	Community Charter (British Columbia)	Land Use and Planning	Land use and planning, environmental quality, animal and public health
Burt's Constraint (Bridge Acts)	1	Nutrient Management Act (Ontario)	Agricultural Management	Environment quality, animal and public health, land use and planning
	2	Building Act (Quebec)	Oil, Gas and Mining	Land use and planning, oil gas and mining, environmental quality
	3	Safety Codes Act (Alberta)	Land Use and Planning	Land use and planning, environmental quality, animal and public health
	4	Clean Water Act (Ontario)	Environmental Quality	Environmental quality, land use planning, animal and public health
	5	Executive Council Act (Newfoundland and Labrador)	Fisheries and Biodiversity	Environmental quality, land use and planning, climate change

Hub Acts have the shortest paths to all other Acts in the network via shared terms (see Figure 5.1 The network of nutrient-related Acts across Canada. Figure 5.1a and Table 5-2). In part, the hub Acts we identified have many close connections because they tend to be in larger topics with more nodes (e.g. *environmental quality* and *land use and planning*), and therefore have a large number of other similar Acts to connect to. However, these policies also touch on a broad array of issues and are strongly connected to other topics such as c*limate change*, or *public and animal health*, resulting in their central position in the network. The broad-reaching nature of these *environmental quality* and *land use and planning* statutes, and their centrality in the nutrient network, suggests these Acts are already potentially fostering nutrient policy integration among existing legislation and may be key entry points for informing cross-cutting new nutrient policies.

The strongest hub Act in Canada's legislative network is the province of Ontario's Environmental Protection Act (OEPA). The OEPA is the primary pollution control legislation in the province and grants the Ministry of the Environment, Conservation and Parks broad powers to deal with the discharge of any contaminants up to and above amounts that are likely to cause adverse effects. This includes setting limits on ammonia, nitrogen dioxides, and nitrous oxide gas[23]. In addition to multiple connections to other legislation in the *environmental quality* topic, the OEPA performs as a hub in the network by including multiple issues that mention both economic pollution sources and environmental outcomes. For example, one of the goals in the OEPA is the cessation of the use of coal as an energy source. This links the OEPA to *climate change* through terms such as "electricity" and "emission", and to *oil, gas and mining* through terms like "coal" and "contaminant".

We also identified potential "bridging" Acts in the network using Burt's Constraint scores (see Figure 5.1a and Table 5-2). Constrained Acts are those whose connected neighbouring Acts share the fewest common neighbours. Because of this feature, constrained Acts connect parts of the network that would otherwise not be connected. We argue that these 'bridging' types of nutrient legislation have the greatest potential to address opportunities for policy integration across the whole network by connecting core issues that are central to nutrient management. The most constrained Act in the nutrient network is Ontario's Nutrient Management Act (ONMA). The purpose of this Act is to "provide for the management of materials containing nutrients in ways that will enhance protection of the natural environment and provide a sustainable future for agricultural operations and rural development"[24]. The ONMA addresses how nutrients (particularly from manure, but also in commercial fertilizer and municipal biosolids) should be managed during storage and application to farmland. This Act, which appears in the *agricultural management* topic in Figure 5.1, strongly links to *environmental quality* acts through terms such as "sewage" and "farm" and *animal and public health* acts through "licence", and "disease". This shows how legislation specifically focusing on nutrient management may be an important bridge in Canadian environmental policy, creating connections within and across topics that would otherwise not exist.

5.2.3 Similarities and differences in N and P networks

To examine if the networks of legislation that explicitly mention phosphorus (P) or nitrogen (N) reflect the biogeochemical context of these two nutrients in the Canadian environment, we also ran the semantic network analysis on N- and P-specific legislation. 38 Acts explicitly mention both N and P keywords, but more Acts mention only N (n = 36) than mention only P (n = 12) (see Supplementary Materials). The resulting networks identify 5 topics for N and 3 topics for P (see Figure 5.2). Compared to the full network (Figure 5.1) these sub-networks omit prominent topics, especially *animal and public health,* and some Acts are assigned to a single group, such as *agriculture and environment* (which formed two separate topics, *agriculture management* and *environmental quality*, in the full network). Both N and P networks cover *occupational health and safety* and *oil gas and mining*, however since only N is relevant to climate change through nitrous oxide emissions, only the N network included *climate change* and *vehicles* (including NO_x) as topics (see Figure 5.2).

There are some key similarities between the structure of the full (Figure 5.1) and nutrient-specific (Figure 5.2) networks. For example, environment protection Acts serve as hubs in all three networks. British Columbia's Environmental Management Act and Nova Scotia's Environment Act were the top two ranked Acts for the closeness measure for both N and P (see Figure 5.2). The most constrained Act in both networks is the Ontario's Nutrient Management Act, mirroring trends observed in the full nutrient legislation network from Figure 5.1.

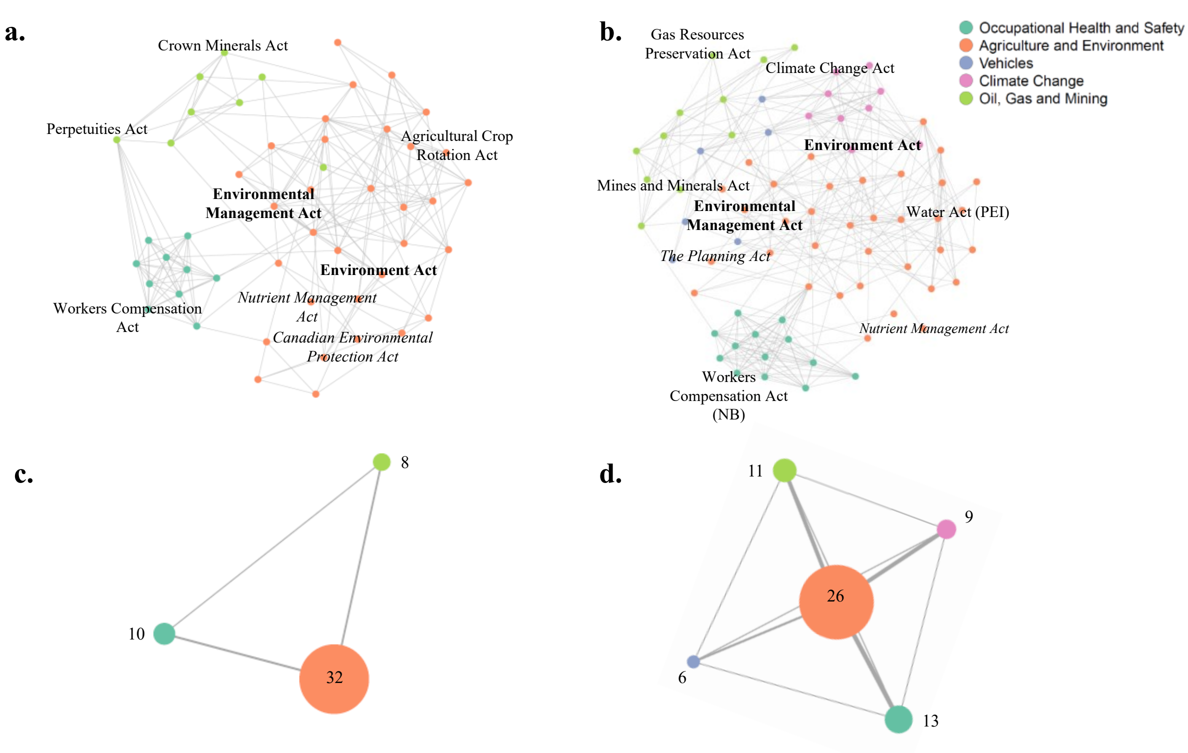

Figure 5.2 Phosphorus (left side, a and c) and nitrogen (right side, b and d) related policies across Canada depicted as network graphs. Edges have been trimmed for visual clarity. Several nodes are labelled to show examples of Acts in each topic group. Act titles that are ***bold*** *are the top 2 "close" hub Acts, italicized are the top 2 "constrained" bridge acts. Graphs c. and d. are contracted networks that simplify the connections between group of Acts. The size of a node represents the number of Acts in the topic group, and the edge thickness represents the weight of the combined edges between Acts in two groups.*

5.2.4 Role of indirect legislation in novel nutrient policy integration

There is increasing need to integrate nutrient policy beyond direct agricultural operations on farms and farm management[5,25]. Our analysis suggests that policies with indirect relevance to nutrient management may provide the greatest opportunities for new policy integration by expanding the range of topics in the policy network. To this end, many of the 245 Acts we identified in the full network indirectly address nutrient management; only about a third (n = 86) of the Acts included in our analysis mentioned explicit nutrient keywords (e.g., 'nitrous oxide' or 'phosphate'), whereas the rest were included because they mentioned other relevant keywords such as 'manure' or 'fertilizer' (see Supplementary Materials for full list of Acts and keywords). The largest number of the nutrient-focused Acts in Figure 5.1 are in the *environmental quality* topic (n =21), reflecting the emphasis on nutrient management with regards to environmental protection in Canada.

Two examples of considerable potential for nutrient policy integration are the topics *land use and planning* and *food marketing and regulations*, as they contain a relatively large number of Acts in total and a relatively small share of the nutrient-focused Acts shown in Figure 5.2. *Land use and planning* (n = 38) is also the largest topic group in the full network, mainly including Acts that assign municipal responsibilities and powers. Only 4 Acts in this topic explicitly mention nutrient-focused keywords, but they commonly mention terms such as "wastewater" (mentioned in 17 *land use and planning* Acts), "manure" (15), and "fertilizer" (11). Rules, regulations, and bylaws around management of these amendments at the municipal level, which are often focused on disease and nuisance control and prevention, have considerable potential for further nutrient policy integration. For example, British Columbia's Local Government Act, the second most 'close' hub in the full network (Table 3-1), mentions bylaws regarding waste and sewage management for protection of water quality despite not explicitly referencing management of nitrogen or phosphorus. This can be compared to Manitoba's The Planning Act, also classified as a *land use and planning* statute, but which explicitly mentions nutrient management. For example, the statute mentions nitrogen management in goals to minimize loss of soil nutrients using strategies such as stormwater retention and treatment, and erosion control.

The *food marketing and regulations* topic also often mentions manure (11) and wastewater (6), but seldom includes nutrient-focused keywords (only mentioned in 2 of 13 texts in this group). This topic addresses issues such as food processing, pricing, packaging, and distribution. Constraints created by economic and regulatory pressures surrounding food production (e.g., licensing requirements, production contracts) have been shown to potentially limit the options farmers have available to them in terms of environmental stewardship[26]. Yet, our results suggest that there is potential to leverage existing regulatory policies in Canada to encourage more sustainable nutrient management options across the food system. For example, linking downstream food waste and manure disposal with upstream aspects of feed and fertilizer management on farms (e.g. most *food marketing and regulations* Acts simply state that manure needs to be removed regularly from slaughterhouses, not what happens to it after)[25,27]. Such opportunities may be especially apparent for the dairy sector, which is one of the main sources of manure nutrients in Canada[28]. Indeed, many *food marketing and regulations* focus on the dairy industry and dairy manure management regulations (5 of 13 Acts).

5.2.5 Alternative network classifications and uncertainties.

Topics can be grouped into larger umbrella groups or smaller subtopics based on the "resolution factor" of the clustering algorithm, so we tested alternative network structures by using different resolution factors to reveal sensitivity of within-topic groupings and potential similarities and synergies among the Acts. For example, with a lower resolution specified (a network with fewer topic groups), *fisheries and biodiversity* Acts and *animal and public health* Acts from our full network (Figure 5.1) are instead combined because of shared terms (e.g., "animal"). At a higher resolution, the broader *environmental quality* topic is separated evenly into two groups: those dealing with environmental protection and assessment (14 Acts linked through common terms like "project", "waste", "environment", and "assessment") and those related to water quality (22 Acts linked by terms such as "water", "contaminant", "wetland", and "aquifer") (see Supplementary Materials for a full list of Acts assigned to each topic with different resolution factors).

Inventories are the first step in understanding the state of existing nutrient policies and for identifying potential synergies or gaps. Yet, our assessment of connections among policies is somewhat complicated because of how legislation is written. For example, the Federal Canadian Environmental Protection Act sets limits on ammonia emissions at the national level, which are not reiterated in provincial legislation unless stricter regulations are being enacted. Therefore, our findings may not reflect the true 'intensity' of nutrient policy in Canada. Our focus on national and provincial Acts may also miss government documents promoting beneficial management practices or nutrient-related policies at the municipal level (e.g., reducing N_2O emissions from cities).

5.3 Toward greater nutrient policy integration

Our analysis identified Acts that are potential policy 'bridges' and 'hubs', both of which offer opportunities to link themes in the existing Canadian nutrient legislative landscape. By examining Canada's nutrient legislation as a semantic network, our study offers a unique approach to identifying potential entry points for nutrient policy integration both in the Canadian context and beyond. For example, innovative new national policies can be informed by subnational (provincial) legislation that already exists. Existing policies could also be better integrated and coordinated, for which the 'hub' and 'bridge' legislation identified in our analysis represent areas to prioritize (Figure 5.1a).

Our findings reveal existing nutrient-focused policies that already represent integral parts of the nutrient policy landscape in Canada (e.g., Ontario's Nutrient Management Act), which could help inform policy development in other countries. A network perspective further shows links between existing nutrient-focused policies and those with more indirect handling of nutrient themes, where there could be potential for policy integration by focusing on peripheral issues (such as land use planning and food processing) that were not intended to address nutrient management but that are nonetheless important areas for new nutrient policy beyond the farm[25]. Future research could explore this further, for example, by applying semantic network analysis to identify policy synergies (e.g. limiting manure application for nuisance and health purposes works well with limiting manure for nutrient management) through directed network analysis or sentiment analysis[5,20]. A basic principle of effective governance is that policies should be coherent with one another, yet a key challenge for nutrient sustainability is the problem of policy coordination and patterns of conflicting interaction, especially given well established trade-offs between food production and multiple environmental impacts[29]. Improving our knowledge of how different policies interact is a first step to moving towards better nutrient sustainability.

5.4 Methodology:

5.4.1 Identifying Nutrient-Related Legislation

To identify relevant texts for analysis we performed a keyword search of the Canadian Legal Information Institute (CANLII) database (https://www.canlii.org/), which contains the consolidated statutes and regulations of every jurisdiction in Canada[30]. Statutes, also known as Acts, are written laws that have been passed by federal or provincial governments. In Canada, most legislation relies on Regulations for implementation, which are authorized through Acts. We therefore searched for national and provincial Consolidate Statutes and Regulations that were in effect as of January 1, 2022, and then cross-referenced the Acts and Regulations. This ensured that if the main text of an Act did not include a keyword, but an associated Regulation did, the Act was still included in our analysis (Figure 5.3). We used 22 keywords informed by previous nutrient policy studies[5,10] including their stemmed variants (nitrogen, nitrous oxide, nitrogen oxides, nitrate/ite, ammonia/ium, phosphorus/ate, nutrient, wastewater, effluent, manure, fertilizer, compost, greenhouse gas, climate change, water pollution, water quality, eutrophication, hypoxia, air pollution, air quality, soil quality, ozone).

We then screened the Acts for relevance to nutrient management. The following were excluded because they only mention nutrient keywords in relation to very specific circumstances. We excluded Acts dealing regulating nitrous oxide in medical uses, littering in provincial parks, swimming pool chemicals, explosives storage or transportation, and Acts prohibiting the addition of nitrous oxide to fuel. To maintain a consistent jurisdictional and geographic scope across our analysis we also omitted Acts that were aimed at local or regional applications (e.g. Lake Simcoe Act, City of Winnipeg Act). We also further refined the documents and did not include any Acts that only included the name of another Act (e.g. a piece of legislation that was only included because it referenced the Nutrient Management Act). After this screening process (Figure 5.3), our analysis included 245 Acts (see Supplementary Materials for full list of Acts used in the analysis).

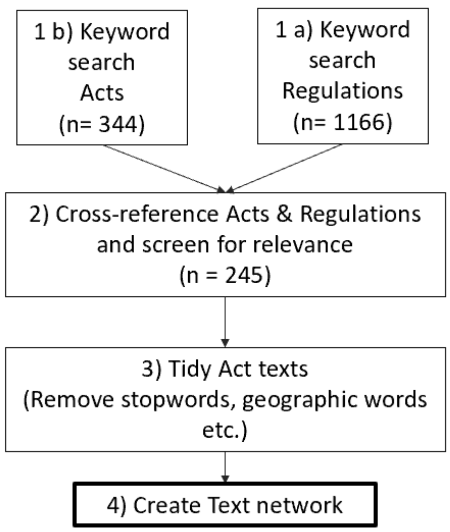

Figure 5.3 Flow chart depicting process of Act selection and screening for the semantic network analysis in this study.

5.4.2 Semantic Network Analysis

To perform the semantic network analysis, we first created a corpus from the text of each Act. The texts were then tokenized and lemmatized, a process that replaces each word with its most basic syntactic form, or "lemma" (e.g. running becomes run). We then removed stopwords, numbers, symbols, short words (those under 3 characters) and geographic words (e.g. Canada, Manitoba, Hudson) to ensure location-invariant grouping. This helps reduce unnecessary content and 'noise' from the text analysis (see Supplementary Materials for list of removed words)[31].

We then ran the texts through a text network program Textnet[17]. The edges (common words) between each Act were weighted according to the sum of the term frequency inverse document frequency (TFIDF) for co-occurring words. This weighting dampens the effect of common but less meaningful words. Acts were clustered into topic groups using the Leiden detection algorithm[32], then manually checked by the authors for cohesion. To examine the effect of the 'resolution' variable, which allows for identification of more or fewer topics groups, we ran the clustering algorithm using a value of 1 (the standard value), 1.7 (the lowest resolution needed to identify groups of only 1 Act), as well as the middle value between these (1.35).

To identify policy hubs and bridges we used two common measures of network centrality:

1) "Closeness centrality", which measures the shortest paths required to reach every other node (Act) in the network[15], in this case the shortest paths being the edges with the highest TFIDF between documents. A node is considered a "hub" when its closeness value is relatively lower than other nodes in the network.

2) "Burt's constraint", which identifies nodes that fill structural holes in the network. This measure captures the extent to which a node has access to many other non-redundant nodes (i.e., a node's neighbours do not share common neighbours). A node is considered a "bridge" when it's relative constraint value is lower than other nodes, indicating it has fewer redundant connections to other nodes and therefore acts as an important link[14].

We also tested network centrality in terms of the "Betweenness centrality" measure[33], which shows nodes that have the greater number of shortest paths traveling through them to other nodes in the network. However, we chose to focus on the above two measures of centrality here because the “betweenness” measure was especially sensitive to the length of the text in an Act and primarily highlighted Acts with a very short body of text.

Finally, to examine the similarities and differences between Acts oriented towards specific nutrients, we also ran the text network analysis for Acts that only explicitly included nitrogen-related keywords (nitrogen, ammonia/ammonium, nitrous oxide, nitrogen oxides, nitrate/ite) (n = 74) and phosphorus-related keywords (phosphorus, phosphate) (n = 51) again using the Leiden clustering method and a resolution of 1.35. A full list of all Acts identified can be found in the Supplementary Material.

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Open Research and Data Availability Statement

All analysis was done using R version (4.0.4)[34]. The R scripts and data used to execute the analyses in this paper are preserved at Figshare[35], under CC BY 4.0 license.

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Chapter 6 Discussion

My findings show clear difference in provincial N_r emissions that are driven by underlying geography, as well as parallels in terms of legislative attention to different sources of N_r across provinces (e.g., oil extraction legislation in Alberta). For example, I found three distinct areas of Canada that show similar characteristics within their region in terms of wastewater treatment, food production and energy sources: *coastal areas* (the Atlantic provinces of New Brunswick, Prince Edward Island, Nova Scotia and Newfoundland and Labrador, as well as British Columbia), the *prairie provinces* (Alberta, Saskatchewan, and Manitoba), and *central Canada* (Ontario and Quebec). In this chapter, I elaborate on the results from the previous three analysis chapters and the distinctions in sources of N_r emissions between regions in Canada. I compare the major sources and drivers of N_r emissions identified by using different methods in Chapters 3 (an N footprint model, a consumption perspective) and 4 (a synthesis of national and provincial emissions inventories, a territorial accounting perspective). I also include additional examples of relevant legislation that I was not able to discuss in Chapter 5 due to length constraints. Finally, I expand on the important role Canada plays as major global exporter of goods and resources.

6.1 Comparing Prairie and central provinces: production vs consumption

There are multiple ways to assign responsibility for emissions (as described in Chapter 2). My research in this dissertation has primarily focused on territorial (accounting for direct emissions) and consumption (accounting for upstream emissions) approaches (see A comparison of different accounting perspectives, Figure 6.1). Furthermore, much of my analysis has drawn on the prairie provinces (Alberta and Saskatchewan) and central provinces (Ontario and Quebec) as case study provinces because of their high total N_r emissions and the differences in per capita N_r emissions. Alberta and Saskatchewan have the highest per capita emissions, while the more populous

Ontario and Quebec have among the lowest. Comparing these four provinces provides a clear example of how underlying geography influences N_r emissions. They also present a useful case to compare the different results between accounting methods for provinces with strong natural-resource oriented economies to those with larger populations and overall consumption.

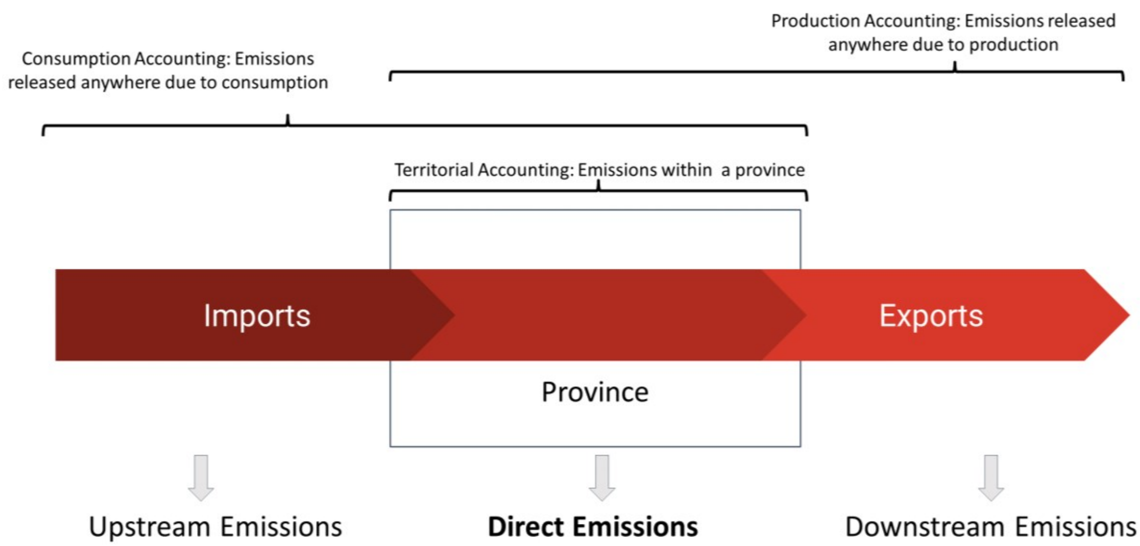

Figure 6.1 A comparison of different accounting perspectives.

The geography of Alberta and Saskatchewan is quite different as compared to Ontario and Quebec. Alberta and Saskatchewan are defined by large flat plains with fertile soils that cover much of southern parts of these provinces. Alberta and Saskatchewan also have underlying sedimentary rock with rich reservoirs of gas and oil. Ontario and Quebec also have fertile soils, especially around the Great Lakes and Saint Lawrence Seaway (see Figure 2.2). However, there are more limited deposits of oil, gas or coal in these provinces.

Because of the availability of fossil fuel deposits and favorable conditions for agriculture, both Alberta and Saskatchewan's economies have very strong fossil fuel extraction and agricultural sectors in terms of share of provincial GDP. Furthermore, these provinces' energy grids are heavily reliant on fossil fuels. Quebec and Ontario have reasonably strong agricultural sectors as well but much larger population centers than Alberta or Saskatchewan (60% of Canada's population lives in these two provinces, and ~40% lives in the just Windsor-Quebec City corridor) and their energy comes predominantly from nuclear energy or hydro.

These differences in geographic and socio-economic characteristics are reflected in differences between the four provinces' N_r emissions as well as in differences between accounting methods. Table 6-1 shows a comparison of the results from Chapter 3's footprint accounting and Chapter 4's inventory-based N_r emissions, by sector for the four example provinces in the year 2017.

Table 6-1 Comparison of total and per capita Nr emissions using an N footprint approach compared to a synthesis of national and provincial emissions inventories. Alberta, Saskatchewan, Quebec, and Ontario were chosen as example provinces as they have among the largest total and per capita N_r emissions. Sectors that have more than a 50% difference in results between the two methods are highlighted in yellow, those with greater than 100% difference are highlighted in orange.

Geography		N footprint (McCourt & MacDonald, 2021)		Territorial (McCourt & MacDonald, 2022)		Difference (%) between N footprint and Territorial	
	Sector	Per capita (kg/cap)	Total (Gg)	Per capita (kg/cap)	Total (Gg)	Per capita	Total
Alberta	Crops	3.8	16.1	7.8	32.8	105%	104%
	Meat	9.4	40.3	15.9	67.1	69%	67%
	Wastewater Treatment	3.0	12.9	2.5	10.3	-17%	-20%
	Energy Generation	5.4	23.1	6.1	25.9	13%	12%
	Oil and Gas Industry	4.0	17.3	27.6	116.3	590%	572%
	Other Industry	2.1	8.9	3.3	13.9	57%	56%
	Transport	11.4	48.8	11.5	48.6	1%	0%
Saskatchewan	Crops	3.7	4.2	49.9	57.0	1249%	1257%
	Meat	9.6	11.2	28.3	32.4	195%	189%
	Wastewater Treatment	3.2	3.6	3.3	3.8	3%	6%
	Energy Generation	9.3	10.8	9.4	10.7	1%	-1%
	Oil and Gas Industry	0.9	1.1	6.4	7.3	611%	564%
	Other Industry	1.3	1.5	1.8	2.1	38%	40%
	Transport	22.5	26.0	22.1	25.4	-2%	-2%
Quebec	Crops	3.8	32.4	1.4	11.6	-63%	-64%
	Meat	8.9	73.9	5.1	58.9	-43%	-20%
	Wastewater Treatment	3.1	26.1	5.3	43.6	71%	67%
	Energy Generation	0.8	6.6	0.9	7.5	13%	14%
	Oil and Gas Industry	0.01	0.1	0.1	0.7	700%	600%
	Other Industry	1.2	10.1	1.3	10.7	8%	6%
	Transport	5.9	49.2	6.0	49.8	2%	1%
Ontario	Crops	3.7	38.9	1.4	19.0	-62%	-51%
	Meat	9.5	134.5	4.0	55.7	-58%	-59%
	Wastewater Treatment	3.1	43.8	3.0	41.5	-3%	-5%
	Energy Generation	0.8	11.7	0.8	11.8	0%	1%
	Oil and Gas Industry	0.02	0.4	0.1	2.5	400%	525%
	Other Industry	1.0	13.5	1.0	13.8	0%	2%
	Transport	4.0	56.2	4.1	56.8	2%	1%

Alberta and Saskatchewan, which have most of the agricultural land in Canada, but relatively small populations, have much larger total and per capita territorial crop and meat related emissions as compared to their footprints associated with crop and meat consumption (more N_r emissions are associated with the production of agricultural goods than consumption in these two provinces). For example, territorial total and per capita N_r emissions associated with meat consumption and production are ~70% larger in Alberta as compared to footprint accounting, and ~200% larger in Saskatchewan. Conversely, Ontario and Quebec, which have a reasonably strong agriculture sector as a share of Canada's total output but a much larger population than Alberta or Saskatchewan, have higher footprint N_r emissions than production emissions for food-related sectors (e.g., total territorial N_r emissions associated with crop consumption and production are 64% and 51% smaller than Quebec and Ontario's meat consumption footprints, respectively).

Territorial emissions for the oil and gas industry are also much higher as compared to the footprint approach across all four provinces (total territorial emissions for oil and gas industry are 572%, 564%, 600% and 525% higher than consumption emissions for Alberta, Saskatchewan, Quebec, and Ontario respectively). In both Alberta and Saskatchewan, which are the main producers of oil and gas in Canada, this is because of the amount of oil and gas extracted and exported. However, this trend is also true in Ontario and Quebec, even though total and per capita territorial oil and gas emissions are much smaller as compared to the western provinces. There are no significant oil fields in Ontario or Quebec, however there are several large oil and gas refineries which refine crude oil and gas imported from western Canada, which is then exported to the US Midwest and eastern Canada (Canada Energy Regulator, 2021).

Legislation in these provinces also broadly follow the consumption and production trends mentioned above. For example, Ontario, with its large population and N footprint, has begun to enact legislation that is oriented towards forming a circular economy and reducing waste streams. The province enacted both the Resource Recovery and Circular Economy Act and the Waste diversion Transition Act in 2016. These laws have the goal to protect the natural environment and human health, minimize greenhouse gas emission, increase opportunities and markets for recovered resources through the reuse and recycling of waste across all sectors of the economy (Resource Recovery and Circular Economy Act, 2016, 2016).

While currently most regulations associated with these Acts focuses on electronic waste and hazardous materials, there is potential here to expand the legislation to be applicable to nutrients. With both large population centers and a strong agricultural sector, Ontario has the capacity for nutrient circulatory at the "bioregional" scale, where producers and consumers can engage more easily due to similar ecological and social characteristics (Harder et al., 2021). In fact a recent study showed that Ontario's inorganic N and P fertilizer inputs to agriculture could be reduced by ~13% and 19% respectively if its current organic waste diversion was increased by 30% (Boh & Clark, 2020).

On the other hand, Saskatchewan recently enacted the Chemical Fertilizer Incentive Act. This legislation gives a tax credit on capital expenditures for new or expanded chemical fertilizer production facilities (The Saskatchewan Chemical Fertilizer Incentive Act, 2020). Saskatchewan already produces the majority of potash fertilizer in Canada, but had only one out of Canada's 11 nitrogen production plants (Alberta on the other hand has 8) (*Canadian Fertilizer Industry: Keeping Canada Growing*, 2021). This Act is already having an effect. Northern Nutrients Ltd.

announced plans to build a sulfur-urea plant, the first non-potash fertilizer manufacturing plant in Saskatchewan since 1992 (Pratt, 2021).

There is no one "right way" to account for N_r emissions and using several accounting methods provides a multi-perspective view that is helpful in obtaining a holistic picture of drivers of N_r emissions. Using different methods also provides different insights into the responsibility for managing emissions. N footprints focus on changing consumer behaviour, whereas provincial inventories focus on the contribution of different economic sectors within the borders of the province. For example, this comparison of results shows that consumption-oriented education, like food labelling and encouraging people to eat less meat, may be more impactful in reducing N_r emissions in the case of Ontario or Quebec. Alternatively, because territorial emissions tend to be much higher in Alberta and Saskatchewan, a focus on more efficient food production might be a better option. Of course, multiple interventions are often needed, but multi-perspective analysis such as this can provide additional insight into what options might be the most targeted.

6.2 Producer-consumer responsibility: accounting for exports

In addition to consumption and territorial accounting, there is also 'production accounting' which is also known as the 'extraction based principle' (Steininger et al., 2016). This approach is often used in relation to carbon and fossil fuel accounting, in the case of N_r it means that the country or area which first creates new N_r would be responsible for all downstream emissions, including after export (see Figure 6.1). While this accounting perspective was outside the scope of my dissertation, I think it is worthwhile to discuss the broad implications taking this accounting perspective has for Canadian N_r mitigation responsibility.

Canada has aggressive growth goals for several economic sectors that are traditionally N_r intensive and export-oriented, including agricultural production and fossil fuel extraction suggestion that there should be additional policy focus on production accounting in Canada. This is especially true in the provinces of Alberta and Saskatchewan which export most of the agricultural goods and fossil fuels produced in Canada, and where the agricultural sector is considered to have some of the highest economic growth potential (Agriculture and Agri-Food Canada, 2021).

Both Alberta and Saskatchewan have laid out provincial growth strategies that rely strongly on increasing output from the agricultural and oil and gas sectors. In Saskatchewan, 11 of the 30 goals set out in the province's growth plan relate to increasing agricultural output and increasing exports. For example, by 2030 the government wants to increase crop production to 45 million metric tonnes (from 35.4 MMT in 2018) and increase oil production by 25 per cent (to 600,000 barrels per day) (Government of Saskatchewan, 2020). In Alberta, the government has plans to expand primary agriculture commodity exports by 7.5% by 2023 (Government of Alberta, 2020a), and to grow oil sands production from 3.1 million barrels per day (bbl/d) to 4.0 bbl/d by 2029 (Government of Alberta, 2020b). All these goals will most likely increase N_r emissions in these provinces.

Encouraging the export of food and other goods not only has the potential to increase direct N_r emissions associated with food production and fossil fuel extraction, but also indirect emissions associated with the transport of these goods. For example, Saskatchewan's top export destinations outside of the United States are China, Japan and India, and the goods travel to these countries primarily by shipping (Government of Saskatchewan, 2020). Shipping is a relatively 'dirty' form of transport in terms of N_r emissions because it is generally powered by low-grade fossil fuels, producing more NO_x than other fuel types. Marine shipping has been a difficult area to regulate in terms of emissions reductions and has seen fewer improvements than other transport sectors like personal vehicles. This difficulty is partly due to the international nature of the marine shipping industry: regulations can be more difficult to agree on and are certainly harder to enforce (Cullinane & Cullinane, 2013). Furthermore, some solutions to improve carbon emissions from marine transport may increase nitrogen emissions (e.g., using ammonia as a shipping fuel (Wolfram et al., 2022).

Yet N_r from marine transport and export emissions are not counted towards Saskatchewan's N_r emissions when looking at N footprints or provincial inventories. Marine transport emissions are concentrated in the Atlantic provinces, British Columbia and Quebec (see Figure 3.4 for provincial N footprints and Figure 4.3 for relative N_r emissions by province and source sector), given that they have extensive maritime coastlines and seaports and access to shipping routes. Using an export-oriented accounting perspective could therefore in theory increase the N_r emissions Saskatchewan is potentially responsible for.

Finally, and perhaps most importantly, beyond producing and exporting food and fuel, Canada is a major producer of synthetic fertilizer and is among the top 10 producers of N fertilizer in the world (FAOSTAT, 2016), and there are incentives currently in place to grow this role. The Chemical Fertilizer Incentive Act has the potential to exacerbate N_r pollution by creating more new N_r. However this type of legislation also provides the potential to include a 'technology-forcing' approach to reducing N_r emissions by requiring fertilizers produced in, and exported from, Canada to be enhanced-efficiency (Kanter & Searchinger, 2018). This 'production oriented' approach could result in more efficient NUE throughout multiple downstream supply chains both within Canada, and globally. All this growth potential for producing and using new

N_r suggests that Canada needs to focus on its role as a global producer and exporter of foods, fertilizer and fossil fuels and ensure that the production occurs in a sustainable manner, especially as each sector grows. The role of international and interprovincial trade should be examined closely with an eye to assessing full supply-chain NUE from multiple supply chain perspectives.

In this chapter I discussed differences and trends in underlying provincial geography and how this impacts N_r emissions. I expanded on the results from my previous three analysis chapters and compare the major sources and drivers of N_r emissions when using consumption and territorial accounting methods. I then gave examples of relevant legislation that follow some of these provincial geographic trends. Finally, I discussed a third potential accounting perspective not explored in my research, production accounting, and the important role Canada plays as major global exporter of goods and resources.

Chapter 7 Conclusions and future research

7.1 Original contributions to research

Abundant N_r has been, and will continue to be, essential in growing enough food for the global population. However, N_r in the environment is resulting in serious negative impacts to the environment and human health. Despite the importance of sustainably managing N_r there remain gaps in our understanding of underlying drivers of N_r emissions, and the policy environment in which decisions are made. This thesis responds to several of the gaps in our understanding of drivers of N_r emissions through the three empirical chapters where I examine the role of different factors as drivers of N_r emissions in Canada, and the related nutrient policy landscape. Each chapter has contributed to scholarship by providing novel models and methodologies, drawing an interdisciplinary analysis and synthesis that helps us better understand drivers of N_r emissions in the Canadian context.

In Chapter 3 I build on our understanding of how consumption-oriented N_r drivers vary with different regional geographic contexts across a large country. Specifically, I developed a novel N footprint model for Canada that reflects sub-national geographic variation in production and consumption patterns between provinces, a detail often obscured in previous national scale N footprint studies. Combining top-down and bottom-up approaches I showed that transport, beef consumption, and wastewater treatment are important sources of N_r emissions nationally. Provincial total and per capita N footprints varied widely, largely due differences in reliance on the fossil fuels sector, including emissions from energy generation and the oil and gas industry. This chapter provided novel insights into drivers of consumption oriented N_r emissions, showed the importance of considering subnational variation and local contexts when examining N footprints, and demonstrated the challenges of attributing N_r emissions, especially in export-oriented economies.

Chapter 4 expands on our understanding of how the role of changing economic structure affects whole-economy N_r emissions. I examined the role of several socio-economic factors over time by synthesizing multiple national and provincial N_r emission datasets, as well as agricultural and wastewater statistics to estimate total and per capita N_r emissions trends across Canada's 10 provinces between 1990 and 2017. This chapter also presents the first index decomposition analysis of whole-economy N_r emissions. This analysis showed that while overall N_r emissions have generally been decreasing since around 2000, agriculture has replaced fossil fuel combustion as the largest source of N_r emissions, and in some provinces agricultural emissions are increasing. The decomposition analysis showed that population and affluence have acted towards increasing N_r emissions but have generally been offset by improvements in emission intensity. Changes in economic structure acted as both a positive and negative pressure on N_r changes, depending on the province. This chapter improves our understanding of drivers of N_r emissions by providing a comprehensive assessment of multiple types of N_r emissions over time, as well as a quantitative analysis of the impact of changes in several socio-economic factors on N_r emissions.

Finally, in Chapter 5, I propose the application of a novel methodology to identify areas for new nutrient policy integration, which is relevant not only in Canada but to other jurisdictions worldwide. This chapter was the first example of semantic network analysis being used to assess a nutrient policy landscape and highlight new areas for intervention and improve policy cohesion. I used nutrient-related legislation in Canada as a case study, showing how this new approach can highlight innovative entry points for better policy integration. I created a network of legislative texts linked by shared terms and uncovered important policy groupings. These ranged from agricultural management laws directly involved with nutrient management to more indirectly related food marketing regulations, which may provide relatively easy areas for new nutrient policy integration. I also identified legislation that was acting as "policy hubs" or "policy bridges", and that were strongly connected within the network or creating important links in the network. These types of laws were examples of existing important points of policy integration that could be emulated. This chapter showed the breadth and depth of topics involved in nutrient management, highlighted key differences in nitrogen and phosphorus nutrient legislation networks, and demonstrated a new way to examine policy landscapes in relation to policy integration.

7.2 Directions for future research

In this thesis, I examined underlying drivers of N_r emissions in the context of Canada. My findings raise new questions and present directions for future research.

First, there are several points in which my N footprint model could be expanded to provide new insights into drivers of N_r emissions. Given their relative importance to Canadian N footprints, obtaining additional data related to meat production and consumption should be a priority area. In particular, more refined publicly available data are needed on typical livestock feed types across livestock systems in Canada, as well as on changes in human diets and food waste, to improve calculations of N footprints, including at more local scales. Data on food consumption and waste in Canada is sparse, especially at the subnational level, while some studies suggest that food waste is increasing (Abdulla et al., 2013; Hanson & Ahmadi, 2022). Future research could also incorporate additional non-food agricultural goods, such as crops used for textiles (e.g., hemp and flax) and bioenergy (e.g., canola for biodiesel and corn for ethanol), as well as timber products and pet food.

Second, my thesis highlights the complications in assigning responsibility for export-oriented emissions, an issue of particular importance given that Canada is a major producer and exporter of agricultural goods and oil and gas resources. Complementary approaches to estimating N_r emissions could be used to provide additional insight both at the national level in terms of Canada's role in global N_r emissions, and at the subnational level in terms of interprovincial trade. For example, using environmentally extended input-output tables (which connect environmental losses to flows of goods and services by tracking transaction values between economic sectors and industries) or physical input-output tables (which track the physical flow of goods) could help provide additional understanding into the economic drivers along supply chains and N flows (Liu et al., 2018; Singh et al., 2017). Environmentally extended input-output exist for Canada (*CIRAIG/OpenIO-Canada*, 2022), but physical input-output tables do not.

Third, I examined policy attention to nutrient issues in Canada. My focus was on legislative documents as these are the result of extended focus on an issue. However, there are multiple types of documents that could be examined to assess policy attention including, such as national and provincial economic development strategies, as well as sustainability action plans. Including additional types of documents would provide new perspectives and provide insights into lateral (between government levels, e.g., provincial and municipal) as well as horizontal (between agencies at the same level of government) policy integration. There are also alternative approaches to assessing policy attention that could provide supplementary knowledge, including assessing federal and provincial level spending on different issues that would provide new insights.

7.4 Closing remarks

To better manage N_r, we must develop strategies that balance our need for food, energy, fibers and other basic necessities of life, while managing the impacts of changes in natural biogeochemical cycles that impacts everything from eutrophication to climate change. My research was facilitated by improvements in access to and availability of data that have allowed us to better understand the human drivers of nutrient stores and flows in the environment, but hard numbers alone will not address the complicated factors driving N_r emissions. Scientists must increasingly use diverse approaches that assess and reflect the complexity of actors and interests involved with N_r management, from examining multiple socio-economic drivers, to accounting for geographic context, to examining different accounting perspectives when assigning mitigation responsibility. I have endeavoured to show in my research how Canada provides an example of the importance of factoring in socio-economic and geographic diversity when addressing N_r accounting. I also sought to show how explicitly considering these contextual factors has an important role to play in terms of informing the individual choices, management decisions, and governance needed to reduce N_r emissions. As a key exporter globally of fertilizer, food, and fuel Canada could become a leader in sustainable N production and use.

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Supplementary Materials

Chapter 3 Supplementary Materials

S1 Crops and crop groups included in this study

Nitrogen Footprint sector	**Crop Group**	**Crops**
Virtual nitrogen from crop production	Grains	barley, corn, oats, rye, triticale, wheat
	Roots	beets, carrots, onions, parsnips, potatoes, rutabagas and turnips
	Fruits	apples, blueberries, cranberries, grapes, nectarines, peaches, pears, plums, raspberries, strawberries
	Vegetables	asparagus, broccoli, brussels sprouts, celery, cabbage, cauliflower, sweet corn, lettuce, green beans, cucumbers, green peas, leeks, peppers, pumpkins, spinach, shallots and green onions, squash and zucchini, tomatoes
	Legumes	beans, chickpeas, lentils, soybeans, peas

S2 Provincial food consumption adjustment and statistical analysis

We adjusted data on national per capita food availability from Statistics Canada (adjusted for food losses) by the Canadian Community Health Survey (CCHS) 24-hour dietary recall to account for differences in provincial food consumption patterns. To examine if food consumption was statistically different between provinces, we used a Kruskal-Wallis rank sum test followed by a pairwise Wilcoxon rank sum test.

The following tables provide examples of the results of the adjustment and statistical analysis for beef and milk. For example, the CCHS-N survey appears to over-represent the amount of beef Canadians eat compared to the national per capita food availability of beef.

Food Group	Province	National food availability from Statistics Canada (kg/cap)	Provincial intake from CCHS-N (kg/cap)	Provincial intake based on national availability adjusted by CCHS-N survey (kg/cap)
Beef	Prince Edward Island	12.8	24.3	11.4
	Quebec		24.9	11.6
	Manitoba		27.0	12.6
	Nova Scotia		27.2	12.7
	Canada		27.4	12.8
	Newfoundland and Labrador		27.6	12.9
	New Brunswick		27.6	12.9
	Alberta		28.4	13.3
	British Columbia		28.6	13.3
	Saskatchewan		28.8	13.4
	Ontario		29.1	13.6
Milk	British Columbia	42.1	43.3	36.9
	Nova Scotia		46.3	39.5
	Ontario		46.8	39.9
	Canada		48.6	41.4
	Alberta		48.7	41.5
	Quebec		49.3	42.1
	Prince Edward Island		50.6	43.1
	Newfoundland and Labrador		50.6	43.2
	New Brunswick		51.1	43.5
	Manitoba		51.9	44.3
	Saskatchewan		55.3	47.2

Results of Kruskal-Wallis rank sum test for beef and milk. For example, Quebec consumes a statistically significant smaller amount of beef as compared to Alberta, British Columbia, Saskatchewan and Ontario, and a larger amount of milk than British Columbia, Nova Scotia, Ontario, and Alberta.

	Alberta	British Columbia	Manitoba	New Brunswick	Newfoundland Labrador	Nova Scotia	Ontario	Prince Edward Island	Quebec
British Columbia	0.82100	-	-	-	-	-	-	-	-
Manitoba	0.21692	0.34408	-	-	-	-	-	-	-
New Brunswick	0.64470	0.72466	0.72466	-	-	-	-	-	-
Newfoundland Labrador	0.72466	0.82634	0.63869	0.84425	-	-	-	-	-
Nova Scotia	0.71119	0.77763	0.65338	0.88039	0.92280	-	-	-	-
Ontario	0.72466	0.64470	0.10804	0.34408	0.54088	0.40796	-	-	-
Prince Edward Island	0.02841	0.04721	0.54088	0.26412	0.19583	0.19583	0.00476	-	-
Quebec	0.00015	0.00048	0.19583	0.06716	0.02841	0.03415	2.4e-06	0.77763	-
Saskatchewan	0.82911	0.72466	0.19583	0.54088	0.64867	0.61092	0.90993	0.02841	0.00048

Kruskal-Wallis test beef consumption. P-value < 0.05 indicates significance.

	Alberta	British Columbia	Manitoba	New Brunswick	Newfoundland Labrador	Nova Scotia	Ontario	Prince Edward Island	Quebec
British Columbia	0.4450	-	-	-	-	-	-	-	-
Manitoba	0.6458	0.9838	-	-	-	-	-	-	-
New Brunswick	0.0296	0.0016	0.0114	-	-	-	-	-	-
Newfoundland Labrador	0.0421	0.0025	0.0195	0.9989	-	-	-	-	-
Nova Scotia	0.9989	0.5238	0.6392	0.0346	0.0421	-	-	-	-
Ontario	0.5062	0.9838	0.9989	0.0016	0.0024	0.5411	-	-	-
Prince Edward Island	0.0636	0.0042	0.0296	0.8941	0.9525	0.0746	0.0042	-	-
Quebec	0.0016	2.1e-06	0.0013	0.8706	0.7952	0.0021	3.9e-07	0.6392	-
Saskatchewan	0.9989	0.5924	0.6821	0.0503	0.0700	0.9838	0.6392	0.1078	0.0056

Kruskal-Wallis test milk consumption. P-value < 0.05 indicates significance.

S3 Wastewater N removal

90% of N in raw municipal wastewater is in Total Kjeldahl Nitrogen (TKN) (Brandes 1978), so we approximated aqueous Nr removal by subtracting final TKN and nitrate and nitrite measurements (mg/l) from initial TKN influent measurements (mg/l) at the following treatment plants. We used septic tanks as a proxy for "no treatment". Studies of septic tanks in Canada have indicated Nr removal (through denitrification) at the range of ~5% (Brandes 1978)

The Jean-R. Marcotte treatment plant in Montreal was used as the example for primary wastewater treatment. It is the largest wastewater treatment plant in Canada by volume of water and serves over 2 million residents. Treatment removes ~25% of aqueous N (MacDonald et al. 2020).

The Ashbridges Bay Treatment Plant in Toronto was used as the case study for secondary treatment. It is the second largest wastewater treatment plant in Canada and serves over 1.5 million residents. Treatment removes ~33 % of aqueous N (*Ashbridges Bay Wastewater Treatment Plant Annual Report* 2018).

The Gold Bar Wastewater Treatment plant in Edmonton was used as the case study for tertiary treatment. Treatment removes ~70 % of aqueous N. (*Annual Wastewater Treatment Report* 2019)

S4 Virtual Nitrogen Factors (VNFs) by province and food group

Canadian Weighted Average VNFs	
Food group	*VNF (g N / kg food)*
Beef	401
Chicken	91
Eggs	52
Milk	12
Pork	106
Fish	61
Fruits	21
Grains	16
Legumes	35
Oilseeds	86
Roots	7
Vegetables	14

Chapter 4 Supplementary Materials

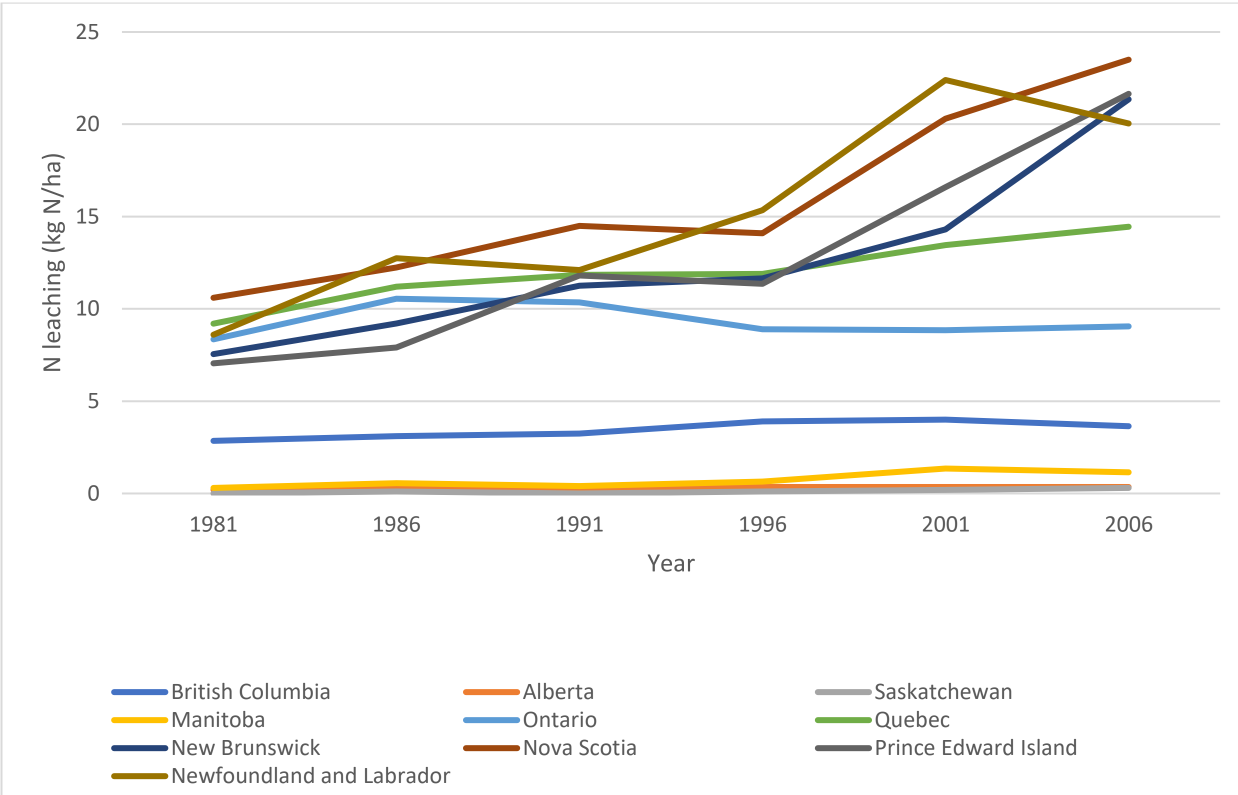

Figure S1. Changes in average provincial agricultural leaching rates (kg N/ha), between 1981 and 2006 (extracted from De Jong et al., 2009).

Treatment Type	Plant name	Province	Year	Annual Effluent Flow (ML)	Average N conc in effluent (N mg/L)	Population Covered	Kg N / cap	Source
Secondary Activated Sludge	Ashbridge	Ontario	2017	240,817	22.1	1,603,700	3.32	(Toronto Water, 2018a)
Secondary Activated Sludge	Ashbridge	Ontario	2018	205,750	23.6	1,603,700	3.03	(Toronto Water, 2018a)
Secondary Activated Sludge	Toronto North	Ontario	2018	6,872	17.2	55,000	2.15	(Toronto Water, 2018b)
Secondary Activated Sludge	Toronto North	Ontario	2017	5,731	17.8	55,000	1.85	(Toronto Water, 2018b)
Secondary with Biological Nutrient Removal	Gold Bar Wastewater	Alberta	2019	87,976	15.4	800,000	1.69	(EPCOR Water Services Inc., 2019)
Secondary with Biological Nutrient Removal	Gold Bar Wastewater	Alberta	2017	93,027	13.24	800,000	1.54	(EPCOR Water Services Inc., 2019)
Secondary with Biological Nutrient Removal	Kelowna	British Columbia	2018	13,243	6	98,000	0.81	(City of Kelowna, 2018)
Secondary with Biological Nutrient Removal	Kelowna	British Columbia	2019	12,915	5.9	100,000	0.76	(City of Kelowna, 2018)
Primary	Iona Island	British Columbia	2017	205,084	30.28	600,000	10.35	(Metro Vancouver, 2017)
Primary	Iona Island	British Columbia	2016	197,002	29.25	600,000	9.60	(Metro Vancouver, 2017)
Primary	Lion's Gate	British Columbia	2017	30,419	31	180,000	5.24	(Metro Vancouver, 2017)
Primary	Lion's Gate	British Columbia	2018	30,916	26	180,000	4.47	(Metro Vancouver, 2017)

Table S1. Data sources used to create proxy N effluent values used in our analysis. Six major wastewater treatment technology categories used in Canada are represented: 1) primary settling and filtration treatment 2) secondary treatment through activated sludge 3) secondary treatment with biological nutrient removal, and 4) trickling filters, 5) lagoons and 6) septic tanks. Per capita N effluent was estimated by multiplying the average N concentration in effluent (combined Total Kjedhal nitrogen, nitrates, and nitrites) by the annual flow and dividing by the population covered by each facility. We used the average of at least two years or multiple facilities each wastewater treatment type in our calculations to account for yearly variation.

Year	Province	Total yearly N emissions (Gg N)	Kg N / capita	Province	Total yearly N emissions (Gg N)	Kg N / capita
1990	New Brunswick	36	49	Nova Scotia	40	44
1991	New Brunswick	35	47	Nova Scotia	39	43
1992	New Brunswick	34	46	Nova Scotia	40	43
1993	New Brunswick	33	44	Nova Scotia	40	43
1994	New Brunswick	33	44	Nova Scotia	41	44
1995	New Brunswick	33	44	Nova Scotia	41	44
1996	New Brunswick	34	46	Nova Scotia	41	44
1997	New Brunswick	36	47	Nova Scotia	42	45
1998	New Brunswick	37	50	Nova Scotia	42	45
1999	New Brunswick	39	52	Nova Scotia	43	47
2000	New Brunswick	42	56	Nova Scotia	47	51
2001	New Brunswick	41	55	Nova Scotia	47	50
2002	New Brunswick	41	55	Nova Scotia	47	51
2003	New Brunswick	40	54	Nova Scotia	48	51
2004	New Brunswick	39	53	Nova Scotia	47	50
2005	New Brunswick	40	53	Nova Scotia	47	50
2006	New Brunswick	37	49	Nova Scotia	43	45
2007	New Brunswick	36	48	Nova Scotia	42	44
2008	New Brunswick	33	45	Nova Scotia	40	42
2009	New Brunswick	32	43	Nova Scotia	38	40
2010	New Brunswick	32	42	Nova Scotia	38	40
2011	New Brunswick	31	41	Nova Scotia	38	40
2012	New Brunswick	28	37	Nova Scotia	36	38
2013	New Brunswick	26	35	Nova Scotia	35	37
2014	New Brunswick	26	34	Nova Scotia	34	36
2015	New Brunswick	25	32	Nova Scotia	32	34
2016	New Brunswick	24	32	Nova Scotia	31	33
2017	New Brunswick	23	31	Nova Scotia	31	33
1990	NFLD	20	34	PEI	9	66
1991	NFLD	19	32	PEI	8	64
1992	NFLD	19	32	PEI	8	63
1993	NFLD	19	33	PEI	8	63
1994	NFLD	19	33	PEI	9	64
1995	NFLD	19	34	PEI	9	64
1996	NFLD	20	35	PEI	9	65
1997	NFLD	21	37	PEI	9	65
1998	NFLD	21	39	PEI	9	67
1999	NFLD	22	40	PEI	9	68
2000	NFLD	22	42	PEI	11	78
2001	NFLD	23	43	PEI	10	76
2002	NFLD	24	45	PEI	10	75
2003	NFLD	25	48	PEI	10	75
2004	NFLD	23	45	PEI	10	76
2005	NFLD	24	46	PEI	12	84
2006	NFLD	22	43	PEI	11	79
2007	NFLD	22	44	PEI	11	77

Table S2. Yearly total (Gg N) and per capita (kg N capita $^{-1}$) Nr emissions for the four Atlantic provinces: New Brunswick, Nova Scotia, Prince Edward Island (PEI) and Newfoundland and Labrador (NFLD), which are reported as an aggregate in the main paper.

Sector/Sub-sector names used in our study

	Agriculture	*Oil and Gas*
NAICS	Crop and animal production (11A)	Oil and gas extraction (211) Support activities for oil and gas extraction (21311A)
APEI	Animal Production Crop Production	Oil and Gas Industry
GHG	Enteric Fermentation Manure Management Agricultural Soils	Oil and Gas Extraction Petroleum Refining Industries

Table S3. Comparison between North American Industry Classification System (NAICS) economic data, and Air Pollution Emission Inventory (APEI) and Greenhouse Gas Emission Inventory (GHG) Nr emission categories used for the sectoral decomposition analysis in our study. As a result of different subsector definitions/boundaries, there may be slight disparities between our Nr emissions estimates and the corresponding dollar ($) value of economic output.

Chapter 5 Supplemental Materials

Province	Act Name	Keywords	Mentions		Cluster resolution			Topic Name (res 1.35)
			nitrogen	phosphorus	1	**1.35**	1.7	
Alberta	Agricultural Operation Practices Act	nitrate, nutrient, manure, fertilizer, compost	yes	no	3	9	11	Agricultural Management
Alberta	Animal Health Act	manure, effluent, compost	no	no	1	10	12	Animal and Public Health
Alberta	Apprenticeship and Industry Training Act	nutrient	yes	no	3	3	13	Occupational Health and Safety
Alberta	Coal Conservation Act	effluent	no	no	7	8	10	Oil, gas and mining
Alberta	Dairy Industry Act	wastewater, manure	no	no	5	6	7	Food Marketing and Regulations
Alberta	Electric Utilities Act	greenhouse gas	no	no	6	7	8	Climate Change
Alberta	Emissions Management and Climate Resilience Act	nitrate, ammonia, nitrous oxide, greenhouse gas, climate change	yes	no	6	7	8	Climate Change
Alberta	Environmental Protection and Enhancement Act	nitrogen oxides, phosphorus, potash, wastewater, effluent, manure, fertilizer, compost, water quality, ozone	yes	yes	2	5	6	Environmental Quality
Alberta	Forests Act	fertilizer	no	no	7	12	15	Forestry
Alberta	Fuel Tax Act	climate change	no	no	4	4	5	Vehicles
Alberta	Gas Resources Preservation Act	nitrogen	yes	no	7	8	10	Oil, gas and mining
Alberta	Irrigation Districts Act	wastewater	no	no	2	2	3	Land Use and Planning
Alberta	Law of Property Act	phosphorus, potash	no	yes	7	8	10	Oil, gas and mining
Alberta	Marketing of Agricultural Products Act	fertilizer	no	no	5	6	7	Food Marketing and Regulations
Alberta	Mines and Minerals Act	phosphorus, potash, nitrogen, wastewater, effluent, greenhouse gas, water quality	yes	yes	7	8	10	Oil, gas and mining
Alberta	Municipal Government Act	wastewater, effluent, manure, water pollution	no	no	2	2	3	Land Use and Planning
Alberta	Occupational Health and Safety Act	nitrous oxide, nitrate, nitrite, ammonia, nitrogen oxide, phosphorus, potassium, effluent, air quality	yes	yes	3	3	4	Occupational Health and Safety
Alberta	Oil and Gas Conservation Act	nitrogen, effluent, water pollution, air quality	yes	no	7	8	10	Oil, gas and mining
Alberta	Oil Sands Emissions Limit Act	greenhouse gas, climate change	no	no	6	7	8	Climate Change
Alberta	Perpetuities Act	phosphorus, potash	no	yes	7	8	16	Oil, gas and mining
Alberta	Public Health Act AB	effluent, manure	no	no	1	10	12	Animal and Public Health
Alberta	Renewable Electricity Act	greenhouse gas, air quality	no	no	6	7	8	Climate Change
Alberta	Safety Codes Act	wastewater	no	no	2	2	3	Land Use and Planning
Alberta	Surface Rights Act	phosphorus, potash	no	yes	7	8	10	Oil, gas and mining
Alberta	Water Act	effluent, manure	no	no	2	5	9	Environmental Quality
Alberta	Workers' Compensation Act	nitrogen oxide, phosphorus, fertilizer	yes	yes	3	3	4	Occupational Health and Safety
British Columbia	Agricultural Land Commission Act	manure, fertilizer, compost	no	no	2	2	3	Land Use and Planning
British Columbia	Carbon Tax Act	greenhouse gas	no	no	4	4	5	Vehicles

British Columbia	Clean Energy Act	greenhouse gas, climate change	no	no	6	7	8	Climate Change
British Columbia	Climate Change Accountability Act	nitrous oxide, greenhouse gas, climate change	yes	no	6	7	8	Climate Change
British Columbia	Community Charter	effluent, manure	no	no	2	2	3	Land Use and Planning
British Columbia	Drinking Water Protection Act	water quality	no	no	2	5	9	Environmental Quality
British Columbia	Environmental Assessment Act	fertilizer, ammonia, nitrogen oxides, nitrates, phosphorus, effluent	yes	yes	2	5	6	Environmental Quality
British Columbia	Environmental Management Act	nitrate, nitrogen oxides, ammonia, phosphorus, potassium, nutrient, wastewater, manure, fertilizer, effluent, compost, greenhouse gas, air pollution, air quality, water quality, climate change, eutrophication, ozone	yes	yes	2	5	6	Environmental Quality
British Columbia	Farm Practices Protection (Right to Farm) Act	manure, fertilizer	no	no	5	9	11	Agricultural Management
British Columbia	Forest and Range Practices Act	nitrate, fertilizer, water quality, soil quality	no	no	7	12	15	Forestry
British Columbia	Greenhouse Gas Industrial Reporting and Control Act	nitrous oxide, ammonia, wastewater, greenhouse gas, climate change	yes	no	6	7	8	Climate Change
British Columbia	Liquefied Natural Gas Project Agreements Act	greenhouse gas, climate change	no	no	6	7	8	Climate Change
British Columbia	Local Government Act	greenhouse gas, water pollution, air pollution, climate change	no	no	2	2	3	Land Use and Planning
British Columbia	Milk Industry Act	wastewater, manure	no	no	5	6	7	Food Marketing and Regulations
British Columbia	Motor Fuel Tax Act	nitrous oxide, nitrogen oxide, greenhouse gas	yes	no	4	4	5	Vehicles
British Columbia	Private Managed Forest Land Act	nutrient, water quality	no	no	7	12	15	Forestry
British Columbia	Provincial Sales Tax Act	phosphorus, potassium, nitrogen, nutrient, manure, fertilizer, compost	yes	yes	4	4	5	Vehicles
British Columbia	Public Health Act BC	wastewater, effluent, compost	no	no	1	10	12	Animal and Public Health
British Columbia	Riparian Areas Protection Act	nutrient	no	no	2	1	1	Fisheries and Biodiversity
British Columbia	Taxation (Rural Area) Act	effluent, manure	no	no	4	2	16	Land Use and Planning
British Columbia	Water Sustainability Act	effluent, fertilizer, compost, water quality	no	no	2	5	9	Environmental Quality
British Columbia	Workers Compensation Act	nitrate, ammonia, nitrogen oxides, phosphorus, manure, fertilizer, air quality, ozone	yes	yes	3	3	4	Occupational Health and Safety
British Columbia	Zero-Emission Vehicles Act	greenhouse gas, climate change	no	no	4	4	5	Vehicles
Canada	Alternative Fuels Act	greenhouse gas, air pollutant	no	no	4	4	5	Vehicles
Canada	Bank Act	effluent, fertilizer	no	no	2	2	2	Land Use and Planning
Canada	Canada Emission Reduction Incentives Agency Act	greenhouse gas, climate change	no	no	6	7	8	Climate Change
Canada	Canada Foundation for Sustainable Development Technology Act	climate change, water quality, air quality, soil quality	no	no	2	2	2	Land Use and Planning
Canada	Canada Labour Code	ammonia, effluent, water quality, air quality	yes	no	3	3	4	Occupational Health and Safety
Canada	Canada Shipping Act, 2001	ammonia, phosphorus, nitrous oxide, fertilizer, water pollution, air pollution, effluent	yes	yes	1	5	9	Environmental Quality
Canada	Canada Water Act	water quality, effluent	no	no	2	5	9	Environmental Quality

Canada	Canadian Environmental Protection Act, 1999	nitrate, nitrite, ammonia, nitrous oxide, nitrogen oxides, potash, phosphorus, nutrient, greenhouse gas, fertilizer, effluent, wastewater, water pollution, air pollution	yes	yes	4	4	5	Vehicles
Canada	Canadian Net-Zero Emissions Accountability Act	greenhouse gas, climate change	no	no	6	7	8	Climate Change
Canada	Department of the Environment Act	water quality, air quality, soil quality	no	no	2	5	6	Environmental Quality
Canada	Excise Tax Act	greenhouse gas, fertilizer, manure	no	no	4	4	5	Vehicles
Canada	Farm Income Protection Act	fertilizer	no	no	5	6	7	Food Marketing and Regulations
Canada	Feeds Act	ammonia, phosphorus, potassium, nutrient, manure	yes	yes	1	10	12	Animal and Public Health
Canada	Fertilizers Act	nitrogen, phosphorus, potassium, nutrient, fertilizer, manure	yes	yes	1	10	12	Animal and Public Health
Canada	Fisheries Act	nitrate, ammonia, phosphorus, effluent, water quality, manure, fertilizer, wastewater, water pollution	yes	yes	1	1	1	Fisheries and Biodiversity
Canada	Food and Drugs Act	nitrite, potassium, fertilizer, compost, manure	yes	no	1	10	12	Animal and Public Health
Canada	Greenhouse Gas Pollution Pricing Act	ammonia, potash, nitrous oxide, fertilizer, wastewater, greenhouse gas, climate change	yes	no	4	4	5	Vehicles
Canada	Health of Animals Act	effluent, manure, fertilizer	no	no	1	10	12	Animal and Public Health
Canada	Impact Assessment Act	climate change, greenhouse gas	no	no	2	5	6	Environmental Quality
Canada	Income Tax Act	potash, air pollution, water pollution, manure, greenhouse gas, air pollution	no	no	4	2	16	Land Use and Planning
Canada	Plant Protection Act	compost, manure	no	no	1	10	12	Animal and Public Health
Manitoba	Animal Diseases Act	manure	no	no	1	10	12	Animal and Public Health
Manitoba	The Apprenticeship and Certification Act	wastewater	no	no	3	3	13	Occupational Health and Safety
Manitoba	The Buildings and Mobile Homes Act	manure, compost, water quality	no	no	2	2	3	Land Use and Planning
Manitoba	The Climate and Green Plan Implementation Act	nitrous oxide, greenhouse gas, climate change	yes	no	6	7	8	Climate Change
Manitoba	The Crown Lands Act	water quality	no	no	7	8	10	Oil, gas and mining
Manitoba	The Dairy Act	wastewater, manure	no	no	5	6	7	Food Marketing and Regulations
Manitoba	The Drinking Water Safety Act	nitrate, nitrite, wastewater, water quality	yes	no	2	5	9	Environmental Quality
Manitoba	The Efficiency Manitoba Act	greenhouse gas	no	no	6	7	8	Climate Change
Manitoba	The Environment Act	nitrous oxide, nitrate, phosphorus, potash, nutrient, effluent, manure, fertilizer, compost, wastewater, greenhouse gas, water quality, climate change, air quality	yes	yes	2	5	6	Environmental Quality
Manitoba	The Farm Practices Protection Act	manure, fertilizer	no	no	5	9	11	Agricultural Management
Manitoba	The Farm Products Marketing Act	manure, fertilizer	no	no	5	6	7	Food Marketing and Regulations
Manitoba	The Groundwater and Water Well and Related	manure, fertilizer, wastewater, water quality	no	no	2	5	9	Environmental Quality
Manitoba	The Income Tax Act	nutrient, manure, compost, water pollution, air pollution	no	no	4	2	16	Land Use and Planning
Manitoba	The Manitoba Agricultural Services Corporation Act	nutrient	no	no	5	9	2	Agricultural Management

Manitoba	The Oil and Gas Act	nitrogen, potash	yes	no	7	8	10	Oil, gas and mining
Manitoba	The Ozone Depleting Substances Act	ozone	no	no	4	4	6	Vehicles
Manitoba	The Pesticides and Fertilizers Control Act	ammonia, nitrate, nitrogen, phosphorus, potassium, nutrient, wastewater, manure, fertilizer, compost	yes	yes	1	10	12	Animal and Public Health
Manitoba	The Planning Act	nitrogen, nutrient, wastewater, manure, fertilizer, compost, greenhouse gas, air pollution, water quality, soil quality, climate change	yes	no	2	2	3	Land Use and Planning
Manitoba	The Polar Bear Protection Act	climate change, water quality, air quality	no	no	2	1	14	Fisheries and Biodiversity
Manitoba	The Property Tax and Insulation Assistance Act	water quality, air quality, soil quality	no	no	4	2	16	Land Use and Planning
Manitoba	The Public Health Act	nutrient, effluent, fertilizer, manure, wastewater, air quality	no	no	1	10	12	Animal and Public Health
Manitoba	The Retail Sales Tax Act	manure, fertilizer, compost, greenhouse gas	no	no	4	4	5	Vehicles
Manitoba	The Surface Rights Act	nitrogen	yes	no	7	8	10	Oil, gas and mining
Manitoba	The Water Protection Act	ammonia, nitrate, phosphorus, nutrient, wastewater, effluent, manure, fertilizer, compost, water pollution, water quality	yes	yes	2	5	9	Environmental Quality
Manitoba	The Water Resources Conservation Act	climate change, manure	no	no	2	5	9	Environmental Quality
Manitoba	The Wild Rice Act	fertilizer	no	no	7	8	10	Oil, gas and mining
Manitoba	Workplace Safety and Health Act, The	nitrogen oxide, air quality	yes	no	3	3	4	Occupational Health and Safety
New Brunswick	Agricultural Land Protection and Development Act	manure, fertilizer	no	no	5	9	11	Agricultural Management
New Brunswick	Agricultural Operation Practices Act	fertilizer	no	no	5	9	11	Agricultural Management
New Brunswick	Clean Air Act	nitrogen oxide, wastewater, effluent, climate change, air quality, ozone	yes	no	2	5	9	Environmental Quality
New Brunswick	Clean Environment Act	compost, wastewater, effluent, greenhouse gas, climate change, water pollution, water quality,	no	no	2	5	9	Environmental Quality
New Brunswick	Clean Water Act	phosphorus, nutrient, compost, wastewater, effluent, manure, fertilizer, compost, climate change, water pollution, water quality,	no	yes	2	5	9	Environmental Quality
New Brunswick	Climate Change Act	nitrous oxide, nitrogen, greenhouse gas, climate change	yes	no	6	7	8	Climate Change
New Brunswick	Easements Act	wastewater	no	no	2	11	14	Land Conservation
New Brunswick	Environmental Trust Fund Act	climate change	no	no	6	7	16	Climate Change
New Brunswick	Gasoline and Motive Fuel Tax Act	greenhouse gas, climate change	no	no	4	4	5	Vehicles
New Brunswick	Livestock Operations Act	nutrient, manure	no	no	1	10	12	Animal and Public Health
New Brunswick	Local Governance Act	wastewater, manure	no	no	2	2	3	Land Use and Planning
New Brunswick	Mining Act	nitrate, phosphorus, potash, climate change, effluent, air quality	yes	yes	7	8	10	Oil, gas and mining
New Brunswick	Natural Products Act	manure, wastewater	no	no	5	6	7	Food Marketing and Regulations

New Brunswick	Occupational Health and Safety Act	nitrogen oxide, effluent, air quality, water quality	yes	no	3	3	4	Occupational Health and Safety
New Brunswick	Oil and Natural Gas Act	effluent, climate change	no	no	7	8	10	Oil, gas and mining
New Brunswick	Public Health Act	wastewater, effluent, manure	no	no	1	10	12	Animal and Public Health
New Brunswick	Topsoil Preservation Act	wastewater	no	no	1	10	12	Animal and Public Health
New Brunswick	Workers' Compensation Act	ammonia, phosphorus	yes	yes	3	3	4	Occupational Health and Safety
Newfoundland and Labrador	Aquaculture Act	fertilizer	no	no	1	1	1	Fisheries and Biodiversity
Newfoundland and Labrador	Environmental Protection Act	ammonia, nitrogen oxides, manure, fertilizer, effluent, compost, air quality, air pollution, ozone	yes	yes	2	5	6	Environmental Quality
Newfoundland and Labrador	Executive Council Act	greenhouse gas, soil quality, climate change	no	no	2	5	6	Environmental Quality
Newfoundland and Labrador	Farm Practices Protection Act	manure, fertilizer, compost	no	no	5	9	11	Agricultural Management
Newfoundland and Labrador	Fish Inspection Act	effluent	no	no	1	1	1	Fisheries and Biodiversity
Newfoundland and Labrador	Health and Community Services Act,	fertilizer, effluent, manure	no	no	1	10	12	Animal and Public Health
Newfoundland and Labrador	Highway Traffic Act	nitrogen oxides	yes	no	4	4	5	Vehicles
Newfoundland and Labrador	Management of Greenhouse Gas Act	nitrous oxide, greenhouse gas, climate change	yes	no	6	7	8	Climate Change
Newfoundland and Labrador	Mineral Act	water quality	no	no	7	8	10	Oil, gas and mining
Newfoundland and Labrador	Municipalities Act	wastewater, effluent, climate change	no	no	2	2	3	Land Use and Planning
Newfoundland and Labrador	Occupational Health and Safety Act	nitrogen oxides, phosphorus, air quality, ozone	yes	yes	3	3	4	Occupational Health and Safety
Newfoundland and Labrador	Petroleum and Natural Gas Act	greenhouse gas, climate change	no	no	7	8	10	Oil, gas and mining
Newfoundland and Labrador	Urban and Rural Planning Act	compost	no	no	2	2	3	Land Use and Planning
Newfoundland and Labrador	Water Resources Act	nitrate, ammonia, phosphorus, wastewater, effluent, water quality	yes	yes	2	5	9	Environmental Quality
Nova Scotia	Agricultural Marshland Conservation Act	manure, fertilizer	no	no	2	2	3	Land Use and Planning
Nova Scotia	Agriculture and Marketing Act	nitrate, nitrite, ammonia, nutrient, fertilizer, manure, compost	yes	no	5	6	7	Food Marketing and Regulations
Nova Scotia	Anti-idling Act	air pollution	no	no	4	4	5	Vehicles
Nova Scotia	Apprenticeship and Trades Qualifications Act	nutrient	no	no	3	3	13	Occupational Health and Safety
Nova Scotia	Crown Lands Act	climate change	no	no	7	12	15	Forestry
Nova Scotia	Dairy Industry Act	wastewater, manure, water quality	no	no	5	6	7	Food Marketing and Regulations
Nova Scotia	Energy Resources Conservation Act	nitrogen	yes	no	6	7	8	Climate Change
Nova Scotia	Environment Act	nitrate, ammonia, nitrous oxide, nitrogen oxides, phosphate, potassium, nutrient, effluent, wastewater, fertilizer, compost, greenhouse gas, water quality, air quality, air pollution, climate change, ozone	yes	yes	6	7	8	Climate Change
Nova Scotia	Environmental Goals and Climate Change Reduction Act	greenhouse gas, water quality, air quality, climate change	yes	no	6	7	8	Climate Change

Nova Scotia	Environmental Goals and Sustainable Prosperity Act	nitrous oxide, nitrogen oxides, wastewater, greenhouse gas, air pollution, climate change, ozone	no	no	6	7	8	Climate Change
Nova Scotia	Farm Practices Act	fertilizer	no	no	5	9	11	Agricultural Management
Nova Scotia	Farmers Fruit, Produce and Warehouse Associations Act	manure, fertilizer	no	no	2	2	2	Land Use and Planning
Nova Scotia	Fisheries and Coastal Resources Act	effluent	no	no	1	1	1	Fisheries and Biodiversity
Nova Scotia	Forest Enhancement Act	water quality	no	no	7	12	15	Forestry
Nova Scotia	Fur Industry Act	nitrate, ammonia, phosphorus, nutrient, compost	yes	yes	1	10	12	Animal and Public Health
Nova Scotia	Health Protection Act	wastewater, manure	no	no	1	10	12	Animal and Public Health
Nova Scotia	Municipal Government Act	wastewater, effluent, compost, water quality, climate change	no	no	2	2	3	Land Use and Planning
Nova Scotia	Petroleum Resources Removal Permit Act	nitrogen	yes	no	7	8	10	Oil, gas and mining
Nova Scotia	Water Resources Protection Act	climate change	no	no	2	5	9	Environmental Quality
Nova Scotia	Workers' Compensation Act	phosphorus, fertilizer	no	yes	3	3	4	Occupational Health and Safety
Ontario	Aggregate Resources Act	phosphorus	no	yes	7	8	10	Oil, gas and mining
Ontario	Animal Health Act	compost, phosphorus	no	yes	1	10	12	Animal and Public Health
Ontario	Animals for Research Act	nutrient	no	no	1	10	12	Animal and Public Health
Ontario	Building Code Act	nitrate, ammonia, nutrient, wastewater, effluent, manure, fertilizer, compost, air quality, soil quality	yes	no	2	10	3	Animal and Public Health
Ontario	Cap and Trade Cancellation Act, 2018	greenhouse gas, climate change	no	no	6	7	8	Climate Change
Ontario	Capital Investment Plan Act	wastewater	no	no	2	2	2	Land Use and Planning
Ontario	Clean Water Act	nutrient, fertilizer, water quality	no	no	2	5	9	Environmental Quality
Ontario	Conservation Authorities Act	climate change	no	no	2	2	3	Land Use and Planning
Ontario	Conservation Land Act	water quality	no	no	2	11	14	Land Conservation
Ontario	Electricity Act, 1998	nutrient, wastewater, greenhouse gas, climate change	no	no	6	7	8	Climate Change
Ontario	Endangered Species Act	nutrient, wastewater, water quality	no	no	1	1	1	Fisheries and Biodiversity
Ontario	Environmental Assessment Act	wastewater, effluent, water quality, air quality	no	no	2	5	6	Environmental Quality
Ontario	Environmental Bill of Rights	nitrous oxide, greenhouse gas, climate change, air pollution	yes	no	2	5	6	Environmental Quality
Ontario	Environmental Protection Act	nitrate, nitrite, nitrous oxide, nitrogen oxides, ammonia, phosphorus, potash, nutrient, wastewater, effluent, manure, compost, fertilizer, greenhouse gas, climate change, water pollution, air pollution, air quality, soil quality, ozone	yes	yes	2	5	9	Environmental Quality
Ontario	Farm Implements Act	manure	no	no	5	9	11	Agricultural Management
Ontario	Farming and Food Production Protection Act	nutrient, fertilizer	no	no	5	9	11	Agricultural Management
Ontario	Fish and Wildlife Conservation Act	wastewater, effluent, water quality	no	no	1	1	1	Fisheries and Biodiversity
Ontario	Food Safety and Quality Act	nitrate, nitrite, phosphorus, manure, fertilizer, compost	yes	yes	1	10	12	Animal and Public Health

Ontario	Forestry Act	water quality, soil quality	no	no	7	12	15	Forestry
Ontario	Infrastructure for Jobs and Prosperity Act	wastewater, effluent, greenhouse gas, climate change	no	no	2	7	13	Climate Change
Ontario	Milk Act	manure	no	no	5	6	7	Food Marketing and Regulations
Ontario	Mining Act	ammonia, nutrient, effluent, fertilizer, water quality	yes	no	7	8	10	Oil, gas and mining
Ontario	Municipal Act, 2001	climate change	no	no	2	2	3	Land Use and Planning
Ontario	Nutrient Management Act	nitrate, nitrite, ammonia, phosphorus, potassium, nutrient, manure, fertilizer, wastewater, effluent, compost, climate change	yes	yes	2	9	17	Agricultural Management
Ontario	Occupational Health and Safety Act	nitrous oxide, nitrogen oxides, effluent	yes	no	3	3	4	Occupational Health and Safety
Ontario	Ontario College of Trades and Apprenticeship Act, 2009	manure, fertilizer	no	no	3	3	13	Occupational Health and Safety
Ontario	Ontario Water Resources Act	nutrient, effluent, wastewater, water quality, climate change	no	no	2	5	9	Environmental Quality
Ontario	Planning Act	greenhouse gas, climate change, wastewater, effluent	no	no	2	2	3	Land Use and Planning
Ontario	Resource Recovery and Circular Economy Act	nitrogen, phosphorus, potassium, nutrient, compost, fertilizer, greenhouse gas	yes	yes	2	5	6	Environmental Quality
Ontario	Retail Sales Tax Act	fertilizer	no	no	4	4	5	Vehicles
Ontario	Safe Drinking Water Act	nitrate, nitrite, nitrogen, ammonia, phosphorus, nutrient, wastewater, effluent, water quality	yes	yes	2	5	9	Environmental Quality
Ontario	Waste Diversion Transition Act, 2016	fertilizer, climate change	no	no	2	5	6	Environmental Quality
Ontario	Water Opportunities Act	wastewater, climate change	no	no	2	7	8	Climate Change
Ontario	Workplace Safety and Insurance Act	nitrogen oxides, phosphorus, wastewater	yes	yes	3	3	4	Occupational Health and Safety
Prince Edward Island	Agricultural Crop Rotation Act	nitrogen, phosphorus, nutrient, "water quality", "soil quality", climate change	yes	yes	5	9	11	Agricultural Management
Prince Edward Island	Agricultural Insurance Act	fertilizer	no	no	5	9	2	Agricultural Management
Prince Edward Island	Animal Welfare Act	nutrients	no	no	1	10	12	Animal and Public Health
Prince Edward Island	Climate Leadership Act	greenhouse gas, climate change	no	no	4	4	5	Vehicles
Prince Edward Island	Environmental Protection Act	nitrogen oxides, nitrate, nitrite, ammonia, phosphorus, potassium, nutrient, manure, fertilizer, compost, wastewater, effluent, air quality, water quality, water pollution, ozone	yes	no	2	5	6	Environmental Quality
Prince Edward Island	Farm Practices Act	fertilizer	no	no	5	9	11	Agricultural Management
Prince Edward Island	Fish Inspection Act	effluent	no	no	1	1	1	Fisheries and Biodiversity
Prince Edward Island	Institute of Man and Resources Act	fertilizer	no	no	2	2	2	Land Use and Planning
Prince Edward Island	Public Health Act	manure, effluent	no	no	1	10	12	Animal and Public Health
Prince Edward Island	Real Property Tax Act	effluent, manure, compost	no	no	4	2	16	Land Use and Planning
Prince Edward Island	Renewable Energy Act	effluent	no	no	6	7	8	Climate Change
Prince Edward Island	Revenue Tax Act	manure, fertilizer	no	no	4	4	5	Vehicles

Prince Edward Island	Water Act	nitrate, ammonia, phosphorus, potassium, nutrient, wastewater, manure, fertilizer, effluent, water quality, climate change	yes	yes	2	5	9	Environmental Quality
Quebec	Act respecting commercial aquaculture	fertilizer, compost	no	no	1	1	1	Fisheries and Biodiversity
Quebec	Act respecting Investissement Québec	greenhouse gas, climate change	no	no	2	2	2	Land Use and Planning
Quebec	Act respecting land use planning and development	phosphorus, manure, fertilizer	no	yes	2	2	3	Land Use and Planning
Quebec	Act respecting occupational health and safety	nitrous oxide, nitrate, nitrite, ammonia, nitrogen oxide, phosphorus, potassium, wastewater, effluent, manure, fertilizer, air quality	yes	yes	3	3	4	Occupational Health and Safety
Quebec	Act respecting remunerated passenger transportation by automobile	climate change, greenhouse gas	no	no	4	4	5	Vehicles
Quebec	Act respecting the acceleration of certain infrastructure projects	greenhouse gas, climate change	no	no	2	5	6	Environmental Quality
Quebec	Act respecting the conservation and development of wildlife	ammonia, nutrient, fertilizer	yes	no	1	1	1	Fisheries and Biodiversity
Quebec	Act respecting the marketing of agricultural, food and fish products	phosphorus, compost, manure	no	yes	5	6	7	Food Marketing and Regulations
Quebec	Act respecting the Ministère du Développement durable, de l'Environnement et des Parcs	greenhouse gas, climate change	no	yes	6	7	8	Climate Change
Quebec	Act respecting the preservation of agricultural land and agricultural activities	manure, compost, fertilizer, wastewater	no	no	2	2	3	Land Use and Planning
Quebec	Act respecting the Québec sales tax	fertilizer, greenhouse gas, manure	no	no	4	4	5	Vehicles
Quebec	Act to affirm the collective nature of water resources and to promote better governance of water and associated environments	climate change, water quality	no	no	2	5	9	Environmental Quality
Quebec	Act to increase the number of zero-emission motor vehicles in Québec in order to reduce greenhouse gas and other pollutant emissions	nitrous oxide, nitrogen oxide, greenhouse gas, climate change	yes	no	4	4	5	Vehicles
Quebec	Agrologists Act	manure, fertilizer	no	no	2	2	2	Land Use and Planning
Quebec	Animal Health Protection Act	ammonia, manure, fertilizer, water pollution	yes	no	1	10	12	Animal and Public Health
Quebec	Building Act	effluent, wastewater	no	no	2	2	2	Land Use and Planning
Quebec	Environment Quality Act	nitrate, nitrite, nitrous oxide, nitrogen oxide, ammonia, phosphorus, potassium, wastewater, effluent, manure, fertilizer, compost, greenhouse gas, air pollution, water quality, soil quality, climate change, ozone	yes	yes	2	5	9	Environmental Quality
Quebec	Food Products Act	manure, compost, wastewater	no	no	5	6	7	Food Marketing and Regulations
Quebec	Ministère de l'Agriculture, des Pêcheries et de	phosphorus, fertilizer	no	yes	2	2	3	Land Use and Planning

	l'Alimentation, Act respecting the							
Quebec	Municipal Powers Act	manure	no	no	2	2	3	Land Use and Planning
Quebec	Natural Heritage Conservation Act	climate change, effluent, fertilizer, compost	no	no	2	5	14	Environmental Quality
Quebec	Petroleum Resources Act	greenhouse gas, potassium, wastewater	no	no	7	8	10	Oil, gas and mining
Quebec	Retail Sales Tax Act	fertilizer, air pollution	no	no	4	4	5	Vehicles
Quebec	Sustainable Forest Development Act	water quality, climate change	no	no	7	12	15	Forestry
Quebec	Taxation Act	potash, effluent, manure, greenhouse gas, water pollution, air pollution	no	no	4	2	16	Land Use and Planning
Quebec	Workers' Compensation Act	phosphorus	no	yes	3	3	4	Occupational Health and Safety
Saskatchewan	An Act respecting the Management and Reduction of Greenhouse Gases and Adaptation to Climate Change	nitrous oxide, greenhouse gas, climate change, fertilizer	yes	no	6	7	8	Climate Change
Saskatchewan	Fisheries (Saskatchewan) Act	nutrient, fertilizer	no	no	1	1	1	Fisheries and Biodiversity
Saskatchewan	Mineral Resources Act	nitrogen, phosphorus, potash	yes	no	7	8	10	Oil, gas and mining
Saskatchewan	Planning and Development Act, 2007	effluent	no	no	2	2	3	Land Use and Planning
Saskatchewan	Provincial Sales Tax Act	nitrogen, phosphorus, potassium, nutrient, effluent, manure, fertilizer, greenhouse gas	yes	yes	4	4	5	Vehicles
Saskatchewan	Public Health Act SK	air quality, effluent, water quality, manure	no	no	1	10	12	Animal and Public Health
Saskatchewan	Saskatchewan Chemical Fertilizer Incentive Act	potash, nutrient, fertilizer	no	no	1	10	12	Animal and Public Health
Saskatchewan	Saskatchewan Employment Act, The,	nitrate, ammon, nitrous oxide, nitrogen oxides, phosphorus, potassium	yes	yes	3	3	4	Occupational Health and Safety
Saskatchewan	The Agricultural Operations Act,	nitrogen, phosphorus, potassium, manure, fertilizer, effluent, wastewater, water pollution	yes	yes	5	9	11	Agricultural Management
Saskatchewan	The Animal Health Acts	manure	no	no	1	10	12	Animal and Public Health
Saskatchewan	The Conservation Easements Act	water quality	no	no	2	11	14	Land Conservation
Saskatchewan	The Crown Minerals Act	nitrogen, phosphorus, potash	yes	yes	7	8	10	Oil, gas and mining
Saskatchewan	The Environmental Management and Protection Act	nitrate, nitrite, ammonia, phosphorus, wastewater, fertilizer, manure, effluent, greenhouse gas, air pollution, water pollution, water quality water quality, air quality	yes	yes	2	5	6	Environmental Quality
Saskatchewan	The Farm Financial Stability Act	manure	no	no	5	6	7	Food Marketing and Regulations
Saskatchewan	The Forest Resources Management Act	wastewater, water quality	no	no	7	12	15	Forestry
Saskatchewan	The Fuel Tax Act, 2000	fertilizer	no	no	4	4	5	Vehicles
Saskatchewan	The Irrigation Act	effluent, water quality	no	no	2	2	3	Land Use and Planning
Saskatchewan	The Municipal Grants Act	wastewater	no	no	2	2	3	Land Use and Planning
Saskatchewan	The Municipalities Act	effluent, fertilizer	no	no	2	2	3	Land Use and Planning
Saskatchewan	The Oil and Gas Conservation Act	greenhouse gas, climate change	no	no	7	8	10	Oil, gas and mining

Saskatchewan	The Provincial Lands Act, 2016	fertilizer	no	no	7	8	10	Oil, gas and mining
Saskatchewan	The Saskatchewan Water Corporation Act	effluent, water quality	no	no	2	2	2	Land Use and Planning
Saskatchewan	The Water Security Agency Act	water quality	no	no	2	5	9	Environmental Quality