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Essays in International Trade and Environmental Policy

Munzur, Alaz Safak

UNIVERSITY OF CALGARY

Essays in International Trade and Environmental Policy

by

Alaz Safak Munzur

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Abstract

This thesis comprises a collection of three essays on international trade and environmental policy.

In Chapter 1, I examine Britain's trade policy in the 19th century. Britain, the dominant trading nation of the time, abolished protectionist import tariffs in the middle of the century. To quantify the effect of this shift in trade policy on Britain's welfare, I employ a general equilibrium trade model with multiple industries and input-output linkages. Relying on a novel dataset of trade flows and import tariffs of Britain and its main trading partners, I show that trade liberalization improved Britain's overall welfare. This result is driven by the increased volume of trade. Although its terms of trade deteriorated, Britain benefited as its tariff structure became less restrictive over the period.

In Chapter 2, I present an analysis of Canada's commitment under the Paris Agreement. I examine the effects of meeting the emission reduction target as described in Canada's Nationally Determined Contribution on welfare, bilateral trade and carbon leakage at the provincial and national level. To do this, I incorporate pollution emissions as a by-product of production into a general equilibrium trade model. Provinces substantially vary in terms of their economic structures and emissions profiles, therefore the effects of a national environmental policy differ at the regional level. By considering interprovincial trade and linkages across industries, the results provide a comprehensive understanding of how the industry level effects of a national target are transmitted through the Canadian economy and inform the policy in terms of the "emission intensive and trade exposed" industries at the provincial level. Meeting the Paris Agreement target decreases aggregate Canadian output by 0.48% but the provincial effects vary primarily due to differences in emissions intensity of production. Finally, the policy leads to 10.8% of emissions to relocate out of Canada but the proposed Output-Based Pricing System partly alleviates the problem of carbon leakage.

In Chapter 3, using a general equilibrium trade model with cross-border pollution externalities from production, I evaluate the potential for carbon tariffs as an instrument to enforce the commitments under the Paris Agreement. Employing a non-cooperative optimal policy framework, I investigate the strategic interactions across five regions, Canada, China, the European Union, the United States and the rest of the world. In light of the debates following the possible withdrawal of the United States from the Paris Agreement, the analysis specifically focuses on the effects of welfare-maximising carbon tariffs on imports from the United States. I find that optimal carbon tariffs at the industry level result in small reductions in the total emissions and real income of the United States but are not sufficient to enforce participation in emission mitigation efforts. Compared to meeting its emission reduction targets, the United States is better off by withdrawing from the Paris Agreement, bearing the cost of carbon tariffs and retaliating in response. The committing regions are worse off when the United States retaliates. The results show that the negative effects of a worldwide tariff war on real incomes are substantially larger than the compliance cost to the Paris Agreement for all regions.

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Table of Contents

List of Figures and Illustrations

List of Tables

Chapter 1

Welfare Implications of the 19th Century Trade Liberalization in Britain

1.1 Introduction

Britain's comprehensive trade liberalization in the nineteenth century is a central theme of economic history. After decades of political debate, Britain gradually moved toward free trade by simplifying its import tariffs and abandoning the policies of imperial preference that offered colonies privileged access to British markets. With this new trade regime, the goal was to transfer resources to industries in which the country's world lead was greatest, rather than striving for a balance between a secure domestic food supply and the prosperity of its manufacturing industries. The economic consequences of this unilateral shift in policy are not immediately clear and has long been debated in the literature. While increased trade would benefit Britain, higher import demand would deteriorate its terms of trade. The direction of change in Britain's overall welfare requires comparing these opposite forces.

In this paper, I revisit this question and investigate the effect of trade liberalization on Britain's welfare in the nineteenth century. I find that the effect was positive. Britain's welfare increased by 0.80 percent as a result. Although the terms of trade deteriorated, this effect on welfare was smaller in magnitude than the effect of the increase in volume of trade. To quantify the welfare effect of the change in import tariffs, I use a static general equilibrium trade model. The model provides a flexible framework that can accommodate various economic features of the British economy that are observable in the data but have not been fully exploited before in a similar setting such as multiple industries, input-output linkages and industry-level trade elasticities.

When Britain emerged as the leading industrial nation in the eighteenth century, it was an importer of raw materials and semi-manufactured goods and an exporter of finished goods. The import tariffs were set to provide abundant and inexpensive raw materials for the manufacturing industry while manufacturing imports were restricted to protect local industries. As a result, during the trade liberalization of the mid-nineteenth century, the change in average tariffs substantially varied across industries. The literature generally relies on economy-wide average measures of protection and this obscures the relative importance of different industries in total trade.[1] By using tariff-line data, this paper provides detailed results on the effects of trade liberalization across industries. In addition to the uneven imposition of import tariffs in different industries, the inter-industrial linkages also contribute to how the changes in tariffs affect the economy as a whole. To incorporate inter-industrial linkages and data for non-tradable industries in the model, I use the input-output table for Britain in 1841 constructed by Horrell et al. (1994). Therefore, in the set up presented in this paper, a reduction in tariffs affects prices also in the non-tradable industries that use inputs from the tradable ones. Using the input-output table for 1841, the model accounts for how the changes in trade policy in both Britain and the rest of the world spread across industries and affect the whole economy.

This paper also fills another gap in the literature by collecting the bilateral tariffs data

[1]The high variance of Britain's import tariffs across industries is shown in section 1.3.

imposed on British exports by two of its main trade partners, France and the United States.[2] The simultaneous moves of France toward trade liberalization and of the United States toward protection coincides with Britain's shift in trade policy. The effect of trade policies in other countries on British welfare during this period has not been evaluated in the literature. On average, the tariffs on British exports increased. The cost of this increase to Britain was a 0.75 percent decrease in welfare. This decrease in welfare from the increase in average tariffs imposed on Britain's exports was offset by the increase in welfare from the changes in Britain's trade policy. Therefore, although it is by a small margin, Britain was better off as a result of the changes in domestic and foreign trade policies in the second half of the nineteenth century.

There are two strands of literature that contribute to the debate around the impact of Britain's adoption of free trade on welfare.[3] The first one is concerned with the distributional effects of removing high import tariffs, especially on food and raw materials regulated by the Corn Laws and the other one is the effect of tariff reduction on the overall welfare. This paper contributes to this second strand of literature.[4] McCloskey (1980) resparked the debate over the consequences of Britain's unilateral move to trade liberalization in the nineteenth century. McCloskey (1980) argues that Britain may have lost 4 percent of its national income since tariffs were set at a sub-optimal level after the reforms of the 1840s.[5] Harley and McCloskey (2002) argue "in the time of greatest enthusiasm for free trade the usual argument is probably

[2]The tariffs imposed on Britain's exports are limited to these two countries due to data availability.

[3]Britain did not abolish all import tariffs during this period, tariffs on certain revenue raising items like wine were kept high and whether the nineteenth century Britain can be considered a free trader or not is a debated topic in the literature. See for example Nye (1991) who disputes that Britain was a "free trader" because the import tariffs on exotic products, especially on alcohol like rum and wine, were not abolished and had a distortionary effect since beer could be a substitute for these goods, therefore asserts that Britain should be considered protective; and Irwin (1993) for a response to this view, who argues that these tariffs were motivated solely by fiscal reasons and were not protective since there were no domestic substitutes.

[4]For the distributional effects of the repeal of the Corn Laws, see Williamson (1990); for the impact of cheap grain on the income distribution across Europe, see O'Rourke (1997). For a general discussion on the effects of increased integration on equality across countries during this period, see Williamson (1997), Lindert and Williamson (2003), and Williamson (2005).

[5]By making a best-guess calculation, McCloskey (1980) finds the optimal average tariff for Britain in 1841 as 34 percent.

the reverse of the truth: if anything, the move towards free trade in the 1840s and 1850s hurt Britain." With a simple calculation, Harley and McCloskey (2002) assume if the reduction of average tariffs from 1841 to 1881 was fully reflected in export prices, Britain's terms of trade would be reduced by 21 percent and this would reduce national income by about 6 percent. The first attempt to quantify the static welfare effect of Britain's move to free trade in a general equilibrium setting was made by Irwin (1988). Irwin (1988) concludes that a unilateral elimination of tariffs on imports may have cost Britain up to 2 percent of its national income. But the trade partners of Britain did not keep their policies fixed after Britain liberalized and Irwin (1988) agrees that incorporating foreign tariff changes may make significant difference in results. Welfare effect becomes positive in the hypothetical exercise where foreign tariffs were reduced at a similar level as the reduction in Britain. Irwin (1988) emphasizes that the role of foreign trade policies has not been a consideration for the debate on the welfare effects of British free trade movement even though such considerations are essential for the direction of the results. But do these results mean that Britain reformed its trade policy and abolished import tariffs only on ideological grounds at the expense of its welfare? The substantial coverage and magnitude of tariff reductions during the period are difficult to reconcile with British dominance in world trade. Britain could have taken advantage of its pre-eminence in the world economy by imposing high tariffs and therefore maximized its gains from trade if liberalization was damaging for its welfare. Dakhlia and Nye (2004) draw attention to this problem. Employing a general equilibrium model and a set of parameter assumptions to examine the effect of a unilateral reduction to zero of all import tariffs in Britain in 1841, they find a net increase in welfare as a result. Their model consists of a set of goods imported by Britain and three regions, Britain, France and a constructed rest of the world assumed to make up half the world economy, produce and consume the same goods as Britain and France, and impose no tariffs on imports. The direction of the change in Britain's welfare remains the same under alternative parameter assumptions.

The rest of the paper is organized as follows. Section 1.2 provides a brief history of Britain's commercial policy from the protectionist era to liberalism. Section 1.3 describes the sources of data and provides summary statistics on the tariffs and the trade of Britain in the nineteenth century. Section 1.4 demonstrates the general equilibrium model. Using this model and the data, section 1.5 presents the effects of the changes in Britain's and its trade partners' tariff structures on welfare; finally the last section concludes.

1.2 A Brief History of Britain's Move from Protection to Free Trade

Until the second half of the nineteenth century, Britain pursued a highly protective commercial policy. Close and detailed regulation of international trade by a system of prohibitions, high import tariffs and navigation laws was recognized as a tool to prevent food scarcity, control prices and protect local industries. Imports of thousands of articles capable of being brought into competition with domestic production were subject to high tariffs or completely banned. Among all parts of the protective code of Britain, two pieces of commercial legislation deserve special notice: the Navigation Acts which governed every branch of the British commercial shipping, and the Corn Laws which were not simply a set of laws governing the grain trade but affected many aspects of the British economy for centuries. In this section, by mainly focusing on the evolution of these two pieces of regulation through countless petitions and repeals, I present the brief history of the British trade policy in the nineteenth century which was an era dominated by an atmosphere of divided opinion.

During the second half of the seventeenth century, influenced by the mercantilist ideas of the time, Britain passed a series of laws known as the Navigation Acts. The main goal of these acts was to keep foreign countries out of the colonial trade routes and to boost British shipping industry and trade (Harper, 1939, p. 48). The first one of these acts passed under the protectorate of Oliver Cromwell in 1651 prohibited all foreign ships from trading with and within Britain, and required the trade between Britain and the colonies to be carried out by British ships. Despite being rarely enforced, it set the pattern for British policy with regard to trade and navigation for the following two centuries (Fayle, 1918). The Navigation Act of 1660 followed the protectionist principles set forth in 1651. By this act, goods and commodities would be imported into or exported from colonial lands in Asia, Africa or America only in British ships of which the master and three-fourths of the crew had to be British subjects (Raithby, 1819, p. 246). It also 'enumerated' principal colonial products like tobacco, tea, cotton and sugar that were to be traded only with Britain or the colonies. In 1663, the parliament passed a further act that required all imports from Europe bound for the colonies to be shipped first through the ports of England and in ships owned by the British (Raithby, 1819, p. 449). The Navigation Laws were repeatedly revised during the eighteenth century and regulated the British overseas trade until their final repeal in 1849.[6] With these acts, Britain achieved a monopoly over the entire trade of the colonies and British shipowners became the sole carriers of the entire British trade (except the European commodities imported into Britain in ships belonging to the producing country).

Another permanent feature of the international trade history of Britain during the protectionist ages is the Corn Laws.[7] These were a set of laws aimed at protecting local agriculture and regulating food prices by restricting or prohibiting exports and imports of grains. Until the act of 1436, corn exports were either completely prohibited as stated in the act of 1360 or permitted by licence as by the act of 1393.[8] The act of 1436 allowed exports without a

[6]For a detailed account of the politics and the effects of the Navigation Acts, see Clapham (1910), Thomas (1965) and Sawers (1992).

[7]The term "corn" is used to indicate all grains including wheat, oats, rye, barley, malt, peas, beans and maize.

[8]34th Edward III. 1360, c.20 and 17th Richard II. 1393, c.7

license as long as the price of wheat did not exceed 6s. 8d. a quarter[9] and barley 3s.[10] The price levels were later repeatedly adjusted by successive acts during the seventeenth century. Before the seventeenth century, regulating the internal trade and the exports of grain were more important than regulating the imports since during most of the period enough grain was produced to satisfy the country's needs (Barnes, 2013, p. 3). The only act that regulated imports until the mid-seventeenth century was the act of 1463 which allowed the import of corn when prices rose above a certain level.[11] This act became inoperative through time because of the rise in prices and was finally repealed in 1624.[12] Following the restoration of Charles II in 1660, the trade policy underwent a significant change. Until 1660, keeping corn prices at a reasonable level was the main concern, therefore exports were restricted and imports were allowed only to prevent scarcity. After 1660, exports were encouraged and a price band was specified within which certain duties were charged from imports. The acts of 1663 and 1670 set the tone for the acts of this new period governing imports.[13] The act of 1663 was passed to encourage trade, with it a fixed duty was placed on the imported corn and other food items. With the act of 1670, corn exports were permitted at all times (with an export duty in place) and import duties varying with the home price of corn were introduced. But customs collectors needed accurate information on the common market price to administer the law. Before 1780s, there was no central authority that could determine the average corn prices which were essential for a clear calculation of import duties. In 1781, an Inspector of the Returns of Corn was appointed who prepared weekly reports of corn prices and sales which were to be published in the London Gazette (Barnes, 2013, p. 50). This and a better transportation network across the country allowed the government to improve the machinery for administering the trade policy and quickly respond in years of scarcity. The rapid growth of cities with the industrial revolution increased the demand for food more

[9] A quarter of wheat is 217.7 kg.
[10] 15th Henry VI. 1436, c.2
[11] 3rd Edward IV. 1463, c.2
[12] 21st James I. 1624, c.28
[13] 15th Charles II. 1663, c.7 and 22nd Charles II. 1670, c.13

rapidly than the supply and Britain became a net importer of corn in the final years of the eighteenth century (Sharp, 2010).

The steps taken to control the international trade before the nineteenth century were not limited with the restrictions put on the trade of food products. The two main criteria of the protectionist trade policy in this era were to restrict or prohibit the imports of finished goods and the exports of unmanufactured goods in order to maintain industrial primacy in the world. Production of woollen goods was the mainstay of the manufacturing industry until the industrial revolution. To protect the industry, exports of live sheep and lamb were banned in 1565 and exports of wool in 1698.[14] And multiple acts against the exports of unfinished cloth and yarn were passed in 1467, 1487, 1523, and 1541.[15] In order to protect the local cotton and silk industries, imports of textile goods were banned in 1701 and a prohibition on the exports of textile machinery and tools was introduced in 1774.[16] Similarly, imports of silk and leather goods were banned and tariffs on finished goods like paper were increased.[17] In addition to the prohibitive tariffs on imports of "luxury" goods like wine and brandy,[18] additional tariffs ranging between 15-25 percent were imposed on all other imports in 1703-5.[19] These high tariffs on imports of raw materials resulted in protests from the British industrialists (Davis, 1966). In response to the demand from the industry representatives, a comprehensive customs reform in 1722 abolished or reduced the tariffs on some raw materials like dyestuffs, furs, animal skins and spices.[20] Similar measures to grant certain industries exemptions from the raw material tariffs were taken in the following years.

[14] 8th Elizabeth I. 1565, c.3 and 9th & 10th William III. 1698, c.40

[15] 7th Edward IV. 1467, c.3; 3rd Henry VII. 1487, c.11; 14th & 15th Henry VIII. 1523, c.3; 33rd Henry VIII. 1541, c.16

[16] 11th William III. 1701, c.10 and 14th George III. 1774, c.71

[17] 3rd George III. 1763, c.21, 6th George III. 1766, c.19 and 13th George III. 1772, c.61

[18] Even the king was not exempt from paying these duties on luxury goods. As Atton and Holland (1908) mention "The royal baggage on arrival was removed under the seal to Whitehall and three senior land-surveyors attended to examine it. Stringent instructions were issued to collect all duties payable."

[19] 2nd & 3rd Anne 1703, c.9 and 3rd & 4th Anne 1704, c.4

[20] 8th George I. 1722, c.15

The tariffs on undressed flax were repealed in 1731 to encourage the sailcloth industry,[21] on linen yarn in 1756,[22] and on raw silk in 1765.[23] Protecting local industries also involved discouraging the developing industries in the colonies and trade policy was used to achieve that. Development of manufacturing industries in the American colonies during the early eighteenth century was seen as a threat for the trade, navigation and industry of Britain and the colonies were encouraged to produce and export raw materials instead. In his speech delivered in the parliament, Lord Chatham declared that "the British colonists in America had no right to manufacture even a nail for a horseshoe" (Edwards and Young, 1801, p. 467). In 1721, George Oxenden, a member of the House of Commons, emphasized in his address to George I that imports of important articles for the British economy that could not be sourced domestically like naval stores should be carefully managed in order to "divert our colonies from setting up manufactures which directly interfere with those of their mother country" (Cobbett and Hansard, 1811, p. 916). To block the outflow of technology and to prevent rival industries from springing up in the American colonies, exports of machinery and emigration of artisans were restricted. By the act of 1732, exports of hats and felt from American colonies were banned and hat-makers in these colonies were only allowed to take two apprentices at a time.[24] In 1750, "erection or continuance of any mill or other engine for rolling or slitting of iron, or any plating forge to work with a tilt hammer, or any furnace for making steel in any of the said colonies" and exports to the colonies of tools to make iron were prohibited.[25] The Townshend Act of 1767 imposed additional tariffs payable at colonial ports of America on seventy-two items of British manufacture like glass, lead, dyestuffs, paper and also tea.[26] These were levied solely for the purpose of making up for the loss of revenue from the reduction of the rate of land tax in Britain and were met with resistance of the colonial merchants and boycotts of British goods (Dowell, 1888, p. 156).

[21] 4th George II. 1731, c.27
[22] 29th George II. 1756, c.15
[23] 5th George III. 1765, c.29
[24] 5th George II. 1732, c.22
[25] 23rd George II. 1750, c.29
[26] 7th George III. 1767, c.46

Due to the protests and boycotts, the tariffs on manufactured goods were repealed in 1770, but the infamous tax on tea was retained even though it produced an insignificant amount of revenue (Rabushka, 2010, p. 758). These obstructions put in the way of the development of industries in America paved the way of the American independence.[27]

By the end of the eighteenth century, this micro-management of foreign trade together with all the complex and extensive laws enacted through the years under different reigns complicated the customs system and made it very difficult to enforce. By 1760, there were around eight hundred separate acts of parliament regulating customs tariffs (Brewer, 1989). A parliamentary report from 1898 summarizes this problem: "The state of the customs at this period had become such that only a skilful expert could positively say what might be the sum total due upon any particular article or to how many cumulative rates of duty it might be liable." The same report also illustrates the point by enumerating the ten different branches of duty on a "simple" case of imported linen that "had to be painfully built up" for the merchant to pay (British Parliamentary Papers, 1898, p. 14). Critics of this elaborate system claimed that it was hindering the commercial strength of the country and creating an incentive for smuggling. In 1735, the problem was brought up by the opposition in the parliament: "Our trade has suffered more by the domestic improvements made by our neighbours, during the last long tranquillity in Europe, than it has done by any other means, except the heavy duties we have laid upon ourselves, and the great trouble and many fees and perquisites we have subjected our merchants to, both in importing and exporting their goods and merchandise; which incumbrances will in time most certainly ruin every branch of our trade, if we do not take care to remove them speedily" (House of Commons, 1741, p. 413). As the problems created by this complex system were too hard to deny, the simplification of the customs together with the dismantling of the protectionist tendencies of mercantilism

[27]For a review of the role of British trade policy in establishing a common political identity for the American consumer, the non-consumption and non-importation movements of the 1765-1774 and the subsequent demand for independence, see Breen (2005).

would characterize the direction of the trade policy of Britain in the following century.

The nineteenth century began with the Napoleonic wars which lasted almost uninterruptedly from 1793 to 1815. This was a period of interruption in the integration of international commodity markets. From the beginning, both sides tried to prevent the other one from trading with the rest of the world and banned the imports of each other. Ships of neutral countries were subject to risk of seizure, therefore the United States government passed the Embargo Act in 1807 and prohibited its ships from trading in all foreign ports until 1809 (O'Rourke, 2006). The end of the war brought with it a demand for increased import protection in Europe and the United States. The purposes of the protectionist tariffs introduced at the time were to discourage imports from Britain, the industrial leader of the time, and to allow the development of infant industries (Duckenfield, 2017). The United States adopted protective tariffs in 1816 and again in 1824, 1828, and 1842 (Taussig, 1914). France increased the import tariffs in 1814, Spain in 1816, Prussia in 1818, Russia in 1822, Portugal in 1837, Belgium in 1844, and Holland in 1845. Some of these highly protective tariff regimes introduced at the time were specifically designed to target the industries that Britain had a lead in.[28]

Although the tendencies toward nationalism and protectionism were reinforced by the war in Europe, liberal economic thought had been making progress. Adam Smith, James Mill, Jean Baptiste Say and David Ricardo adopted positions in favour of liberalism in international trade and their books became the leading works guiding the policy in this period of transition.[29] During this period, the Corn Laws became almost inoperative since the prices

[28]For a detailed account of the tariff reforms in Europe during this period, see Bairoch and Burke (1989).

[29]Adam Smith systematically gathered the doctrine of free trade in *Wealth of Nations* (Smith, 1776). French economist Jean Baptiste Say, in his book, *A Treatise on Political Economy*, explains prohibitions as an offensive weapon of governments and designates the greed of several classes of merchants and manufacturers who want to keep their privileges as the source of protectionist measures (Say, 1821). James Mill, in his *Commerce Defended* states that imports are advantageous for Britain because "we can buy it cheaper abroad than we can make it at home" (Mill, 1808). In addition to his influential work *On the Principles of Political Economy and Taxation* published in 1817, David Ricardo published an *Essay on the Influence of a Low*

rose to such a high level that only the lowest rate of duty was paid for imports (Sharp, 2010). The wars impeded Britain's ability to import, as a result raised the prices of agricultural goods and raw materials. O'Rourke (2006) calculates the changes in prices during this period. According to his calculations, the relative price of wheat was 47 percent higher during the war than in the thirteen years previously and the relative price of lumber was 121 percent higher than during the four years following the war. The relative prices of colonial goods also increased, pepper was 53 percent and sugar was 43 percent more expensive during the war than before. At the end of the wars with France, a new Corn Law aimed at increasing production and protecting local agriculture against imports was passed.[30] Lord Ripon, who introduced this bill in the parliament, declared that the objective of the bill was to eliminate price fluctuations and maintain high grain prices since to secure enough supply of grain for the whole population, poor lands had to be cultivated but those could not be cultivated if prices were low. And it was better to pay the high prices than depend on imports.[31] According to this new act, wheat imports were prohibited when prices were below 80s. per quarter and admitted free of duty above this. The new act was immediately met with protests.[32] The argument of the manufacturers was that high agricultural prices were increasing demand for labour in agriculture and therefore affecting wages in all industries. This created a conflict between the interests of the manufacturers and the land lords. The advocates of free trade were organized in the Political Economy Club founded by David Ricardo. This group lead the preparation of the Merchants' Petition and in 1820, an influential banker, Alexander Baring presented it to the House of Commons (Tooke, 1820). This was the first organized civil movement toward the transition to free trade in Britain. This petition was also important since it rebutted the reciprocity argument and recommended unilateral actions to remove

Price of Corn on the Profits of Stock in 1815 in which he criticized the Corn Laws and the protection of agriculture (Ricardo (1815) and Ricardo (1951)).

[30] 55th George III. 1815, c.26

[31] Parliamentary Debates, vol. xxvii, p.1100

[32] William Gladstone in his address to the Cobden Club in 1889, remembered this act as "the most odious and nearly the most extreme exhibition of protection in this country" (Gladstone, 1890, p. 15).

prohibitive import duties.[33] The petition resulted in several government inquiries on the foreign trade of the country.[34] As a result of these inquiries, import tariffs on certain raw materials and industrial products were reduced. After being appointed as the president of the Board of Trade in 1823, William Huskisson, a supporter of the free trade policy, began making legislative changes. Import prohibitions on certain manufactured goods were abandoned and were replaced by ad valorem tariffs, hardware was admitted at a tariff of 20 percent, manufactured cotton goods at 10 percent and woollen goods at 15 percent. By the law of 1824, the prohibition on imports of silk goods which dated back to 1765, was changed into 30 percent ad valorem tariffs.[35] Later, he led the preparation of similar pieces of legislation eliminating prohibitions on foreign manufactured goods and reducing high tariffs on raw materials, specifically the ones employed in manufacturing. Even though there were significant modifications in the policy around this time, the tariff system remained heavily protectionist.

The supporters of the Corn Law of 1815 believed that under the provisions of this act, wheat prices could not be reduced below 80s. per quarter. The prices rose above this as a result of a bad harvests in all grains in 1816 which led to large imports. The imported grain together with the abundant harvests until 1821 reduced prices down to 38s. per quarter

[33]The petition states "That freedom from restraint is calculated to give the utmost extension to foreign trade, and the best direction to the capital and industry of the country." and on the reciprocity argument it states "That although, as a matter of mere diplomacy, it may sometimes answer to hold out the removal of particular prohibitions, or high duties, as depending upon corresponding concessions by other states in our favour, it does not follow that we should maintain our restrictions, in cases where the desired concessions on their part cannot be obtained. Our restrictions would not be the less prejudicial to our own capital and industry, because other governments persisted in preserving impolitic regulations...That, upon the whole, the most liberal would prove to be the most politic course on such occasions" (Tooke, 1820).

[34]Between 1820 to 1824, there were twelve reports from select committees appointed to investigate the means of improving the foreign trade of the country (House of Commons, 1834, p. 67). These were very detailed and comprehensive reports and led to improvements in the trade policy. The evidence presented on one of these reports showed that the ships built using Canadian wood lasted less than half the time of those built of Baltic wood importation of which was subject to prohibitive tariffs due to war (*The first report relative to the timber trade from the select committee appointed to consider of the means of improving and maintaining the foreign trade of the country*, 1820). As a result of the suggestions presented in this report, the war duty and the prohibitive tariffs on Baltic wood were eliminated in 1821 (1st & 2nd George IV. 1821, c.37).

[35]5th George IV. 1824, c.21

(Tooke, 1848). Since prices went below the threshold level, prohibition was in effect for most of the period. And as it became obvious that the law was not successful in eliminating large fluctuations in prices, it was finally repealed in 1828. In 1828, the Duke of Wellington's bill passed and became law. It regulated the corn trade and introduced a "sliding scale" of tariffs where they varied inversely with prices.[36] The intention of this act was to maintain a "pivot price" and eliminate excessive fluctuations. According to this sliding scale, the rate of duty on imported grain was calculated weekly based on the average of the last six weeks' prices (Vamplew, 1980). There was no duty on imports, but once imported, all grain was placed in bonded warehouses. Duty was payable only when the grain was released from bond and entered for home consumption. The idea behind this was to eliminate the influence of foreign politics and trade on grain supplies. Throughout the 1830s, abundant crops kept prices low and muted the protests against the Corn Laws. When prices began rising by the end of 1830s, campaigns for free trade began once again. In 1838, the Anti-Corn Law League, a pressure group of manufacturers, was founded in Manchester to campaign against the restrictions on grain trade. They demanded absolute repeal of the Corn Laws. At the root of the Anti-Corn Law League were the economic interests of the cotton industry in Manchester. With mechanization, cotton goods became a major export of Britain but the share of exports in total production of the cotton industry was diminishing.[37] The argument of the cotton manufacturers was that as the Corn Laws were reducing the imports from countries with agricultural surplus, they were also indirectly reducing the opportunities for exporting British manufactured goods to these countries (Bairoch and Burke, 1989, p. 11). The Anti-Corn Law League also suggested free trade as a solution to the difficulties of the lower economic classes in times of bad harvest (Barnes, 2013, p. 240).

[36] 9th George IV. 1828, c.60

[37] Between the years 1760 to 1769, cotton goods made up 2 percent of total exports of the country. In the decade 1800-1809, they accounted for 39 percent and in 1830-1839, 72 percent of total exports (Mathias, 2013, p. 466). Cotton exports made up 56.4 percent of total cotton production in 1829-1831, this share fell to 50.4 percent in 1834-1836 and to 19.8 percent in 1839-1841 (Deane and Cole, 1962, p. 186).

There was a rising concern that protection was destroying Britain's foreign relations. Retaliatory tariffs had been imposed on British exports by Sweden, Belgium, Russia, the United States and France. To emphasize how every European nation was taking action against Britain's protective trade regime, in his speech made in the parliament in 1841, Lord Palmerston, who later was appointed prime minister in 1855, said "Can we hold these doctrines (of free trade) to other nations and at the same time persist in our own restrictive system? France has lately laid an excluding duty upon our needles and fish hooks, for the purpose of protecting that important branch of her own national industry! Belgians too are running wild with the notion of protection and are for excluding by protecting duties almost every commodity which the industry of man can make. When you preach to these foreign nations the absurdity of such practices, they reply it... England has grown prosperous not by means of this fallacious system, but in spite of it" (Hansard, 1841, p. 655). During the tariff debates of the early 1840s, economists and policy makers were divided in terms of the possible welfare effects of a unilateral move to free trade.[38] Since the period of development and rapid growth in the eighteenth century had been associated with protectionism, trade liberalization was a controversial issue. While the opponents of a unilateral tariff reduction claimed this would result in an economic loss for Britain as import demand increased, supporters emphasized that protectionist measures were distortionary and inefficient. One of the main opponents around this time was the economist Robert Torrens. In his letter

[38]When The Economist magazine was first published in 1843 during the heated discussions on the repeal of the Corn Laws and other restrictions on imports, in support of open markets and less restrictions on trade, authors declared in their famous article on free trade "...we cannot secure larger markets without an unrestricted power of exchange, and by this means add to our territory of land, as far as productive utility is concerned, the corn fields of Poland ..., the rich and the endless acres of the United States; to avail ourselves of the vast and rich productiveness of Brazil, Cuba, Java, etc. and thus at the same time that a plentiful and proportionate supply of all the great necessaries of life would be maintained, we should always, in exchange, have a corresponding demand for our increasing productions at home; the equilibrium of the various classes of producers would be restored and maintained... the benefit [of increased transactions] would circulate throughout all classes, and create what is termed a good home trade" (The Economist, 1843, p. 11). The protectionists on the other hand, regularly presented their arguments in periodicals like Blackwood's Edinburgh Magazine and the Quarterly Review. A commentary published in the Quarterly Review on the debate around the free trade issue in 1841 claimed that the proposed reductions in import tariffs would sacrifice the welfare of the people and the means of national defence; that the working classes were promised 'cheap bread' which was in fact a threat of invasion by the serfs of Poland and low wages (The Quarterly Review, 1841, p. 238).

to the prime minister on the proposals in the budget of 1841 to unilaterally reduce tariffs on imports, he asserted that while "an unrestricted interchange of commodities, between different countries, would increase the wealth of the world" (Torrens, 1844, p. 48), "it is by the enforcement of retaliatory duties throughout the ports of the British empire that free trade is to be conquered. It cannot be too often repeated that free trade consists in freedom from restrictions on both sides; nor can it be too frequently enforced, that the abolition of restriction on one side, while retained on the other, renders the country by which import duties are abandoned tributary to the country by which they retained" (Torrens, 1844, p. 67). In his letters to the members of the parliament and the public, he provided analyses to support his claim that a unilateral move to free trade in Britain would harm the economy through a deterioration in the terms of trade and instead Britain should seek opportunities for bilateral tariff reductions (Torrens, 1844).

It was under these circumstances that, in 1842, the prime minister Robert Peel's bill on corn trade passed and it was considered as the first step towards free trade in grain.[39] With this act, tariffs of the "sliding scale" were decreased and preferential rates were given to grain imported from the British colonies. Williamson (1990) calculates that compared to the act of 1828, the tariff fell from 44 to 22 percent at a domestic price of 60s. Around this time, there was a change in perspective concerning food security. Before, imports were allowed in to eliminate scarcity only when the home prices exceeded a high threshold. It was now believed that abolishing the protection of food would facilitate establishing a secure supply. On this change of perspective Imlah (1958) notes "Against the rising needs of the population and the persistent hazard of crop failures, the only genuine security was to develop production and supply from abroad, and this could not be called suddenly into being in the quantities coming to be required in poor harvest years". In addition to this change in the Corn Laws, Peel reduced tariffs on manufactured goods and colonial imports like coffee and timber, repealed

[39] 5th Victoria 1842, c.14

prohibitions on imports of books, and revoked the ban on exportation of machinery which was introduced in 1774.[40] With the budgets passed between 1842 to 1846, Peel's government started a commercial reform, the goal was to remove all import prohibitions, reduce tariffs on raw materials to a maximum of 5 percent, repeal all export duties, and relax most of the protective tariffs (Noble, 1867, p. 13). Another principle followed from then on was to levy import tariffs without any reference to its origin. Duties on 750 articles out of 1200 on the tariff list were abolished or reduced. The main consideration of Peel's reforms was the interests of the British manufacturer. While there still were protective rates on imports of manufactured goods and agricultural produce, protective tariffs on nearly all raw materials were eliminated. Previously prohibited imports of live animals and meat were admitted at protective tariffs. The revenue lost by these reductions were raised by imposing an income tax (Fay, 1940). The decisive turning-point in Britain's foreign trade policy was the repeal of the Corn Laws in 1846 under the administration of prime minister Robert Peel.[41] 1845 closed with a failure of wheat crop throughout Europe and the Irish potato famine, therefore the need to provide food for the people became an urgency. Although there was opposition from the landed classes, it was under these circumstances and the vigorous efforts of the Anti-Corn Law League that the Corn Laws were finally repealed in 1846.[42]

In line with the new trade regime of the country, the Navigation Acts were repealed in 1849. The clauses regarding the coastal trade, however, were kept until their repeal in 1854, from then on all British shipping became open to competition. By the time before their repeal, the protection provided by the Navigation Acts was small since over fifty percent of

[40] 5th Victoria 1842, c.47 and 5th Victoria 1842, c.49

[41] 9th Victoria 1846, c.22. Even though there was a repeal, tariffs on grains were kept until 1869. But after 1846, imports were permitted at all prices.

[42] John Gladstone, father of future prime minister William Gladstone, was opposed to the repeal. He published influential pamphlets to communicate his views. In one of these he said: "A great and hazardous experiment is about to be made, novel in its character and without the support of experience to guide or direct it, embracing and extending over unbounded interests, and pregnant with results that may prove fatal in their consequences" (Gladstone, 1846, p. 30). In the following years of the repeal, the Conservative Party, led by Benjamin Disraeli, introduced several motions in favour of protection but was defeated in the efforts to restore the Corn Laws (Noble, 1867, p. 48).

foreign trade was regulated by exceptions rather than the restrictions imposed by the acts. In addition to this redundancy argument, it was also believed by the government that the British shipping industry was now strong enough to compete. Registered tonnage of British ships had almost doubled in the three decades between 1820s to 1850s and the transition from wood and sail to iron and steam engines was on the way.[43] Still, the repeal was seen by many shipowners as the start of the downfall of British shipping. However, the trends in the following decades contradicted these views. Usher (1928) shows that the tonnages of both British and foreign ships cleared in foreign trade doubled in the decade following the repeal and British ships always dominated Britain's foreign trade until the twentieth century. By 1914, British ships accounted for 45 percent of world's steam tonnage and carried about half of the total sea trade (Fayle, 1918).

Protectionist policies were not completely abolished with the repeal of the Corn Laws and the Navigation Acts. William Gladstone, a supporter of the free trade movement, was the president of the Board of Trade and was a very influential figure during the preparation of the customs reforms of Robert Peel. With his accession to office as the chancellor of the exchequer, it was expected that he would continue with comprehensive reforms in the trade policy of the country. In his budget of 1853, there were further reductions in tariffs on manufactured goods and raw materials; in total 123 articles could now be imported free of duty and tariffs on 133 others were reduced. The protection provided to imports from the colonies was withdrawn by equalizing the tariffs on similar articles imported from foreign countries. The final remnants of the protective duties disappeared with the budget of 1860. The principle of the government was to retain only the import tariffs with the purpose of raising revenue. Guided by this principle of abolishing all protection, the number of articles in the tariff schedule was reduced to 48 while the bulk of the revenue was raised from 15

[43]Steam ships made up 14 percent of the total world tonnage in 1840, compared to 32 percent in 1860 and 49 percent in 1870 (Bairoch and Burke, 1989).

of these.[44] This change in trade policy can be observed in the customs revenue as a share of imports; in the years 1841 to 1845, customs revenue accounted for 27.2 percent of the total value of imports, whereas in 1855 to 1859 it was 15.8 percent. This was also a period of expansion for the British economy. Between 1843 to 1861, British exports increased by 6 percent per annum, the largest rate of growth in exports ever achieved in Britain until the end of the twentieth century. Another important move from the government came with Gladstone's proposal to repeal the tariff on paper imports in 1860. His campaign went ahead with the slogan "Repeal the taxes on knowledge" (The Spectator, 1860). The repeal achieved in 1861 brought a surge in the number of newspapers and an expansion in the number of pages published (Hewitt, 2013, p. 97). The import of paper increased almost three-folds and the number of newspapers increased from 563 to 1271 in the four years following the repeal (Noble, 1867, p. 126). The economic result of Gladstone's free trade policy is also apparent in the increased exports, the value of exports in all branches of the main industries of the country like the metals and textiles production increased in the 1860s. During the period after the abolition of all protective duties until 1870, the volume of British exports increased by more than a third.[45] And during the same period, the annual growth of the gross national product was 2.4 percent. Just before the repeals of 1842, Britain's exports made up 29.1 percent of the total European exports, after the repeals in 1860, this went up to 30.2 percent; similarly the share of British imports in Europe increased from 29.6 to 35.5 percent.[46]

Before analysing the welfare impact of this unilateral move to free trade, using the official statistics, the following section provides a detailed look into evolution of British trade policy in the second half of the nineteenth century starting from the period right before the repeal of the Corn Laws.

[44] These 15 articles are spirits, wine, tobacco, tea, coffee, corn, currants, timber, chicory, figs, fig-cake, raisins, rice, pepper, and hops.

[45] Calculated from Imlah (1958).

[46] Calculated from Bairoch and Burke (1989).

1.3 Measuring Tariff Protection

Most historical studies on British trade policy during the nineteenth century have relied on the data spanning the decades after 1870.[47] As Lampe (2008) points out, data, especially for the decades before 1870, is needed since this is a period of interest for economists with substantial trade expansion happening around the world happening during this time.[48] Previous work on British trade liberalization before 1870s have used evidence on average tariffs for a selected group of years and aggregate data or focused on protection in certain industries.[49] In this section, I construct an annual series of British trade data for the period 1855-1900. The years of import protection right before the repeal of the Corn Laws, 1840 and 1841, which are the only years before 1855 where reliable and comparable data could be found, are also included in the series. The constructed series is highly detailed at the tariff-line level (except 1840 and 1841). The British statistics covered in this paper exclude colonies and only refer to national territories. This section also presents the construction principles of the bilateral tariffs of other countries toward Britain for the years 1841 and 1870 which I use in the quantitative analyses presented in section 1.5.

The dataset is constructed from a combination of primary and secondary sources. The Board of Trade of Britain published the international trade statistics as several volumes in the Tables of Revenue, Population and Commerce of the United Kingdom embracing the period from 1820 to 1852. From 1853, these tables were subdivided into multiple publications. All statistics related to international trade were published in the Annual Statement of Trade

[47]Most frequently cited works for the British trade statistics covering the nineteenth century are Schlote (1952), Gayer et al. (1953), Imlah (1958), Mitchell and Deane (1962), Mitchell (1975), and Mitchener and Weidenmier (2008).

[48]See, Rostow (1978) and Lewis (1981) for the evolution of world trade in the early nineteenth century. Accominotti and Flandreau (2006) report decennial trade growth rates from various sources, according to these numbers, trade growth was accelerating until 1850s and there was a slowdown in growth after this.

[49]See for example McCloskey (1980), Vamplew (1980), Dakhlia and Nye (2004) and Sharp (2010).

and Navigation while there were also separate publications for colonial and foreign statistics. The rest were published as Miscellaneous Statistics. In 1871, the Annual Statement of Trade and Navigation was subdivided and separate publications were created for trade and shipping. The tables in these publications report the value and quantity of bilateral imports and exports, quantities retained for home consumption, and total values of duties collected for each article.[50] The collection of official trade statistics dates back to the publications of the Inspector General of Exports and Imports in 1697, however, the reason for starting the dataset from 1855 is the ambiguous values in official statistics for the previous years. The rates of valuation in the official statistics before that are based on a set of fixed prices called "official values" computed at average prices in 1694.[51] As time went on, prices varied widely from these official values, so in 1798, the declared values of shipments were substituted for official values in the case of exports. Only in 1854, it was decided to compute and report the current prices of imports and the declared values of imports appeared in official statistics only after 1871.[52] Table 1.1 presents the total imports, GDP, amount of duty collected each year in Britain and the number of varieties for each year included in the dataset.[53] As Table 1.1 shows, while there was an increase in the value of imports, tariff revenue was almost

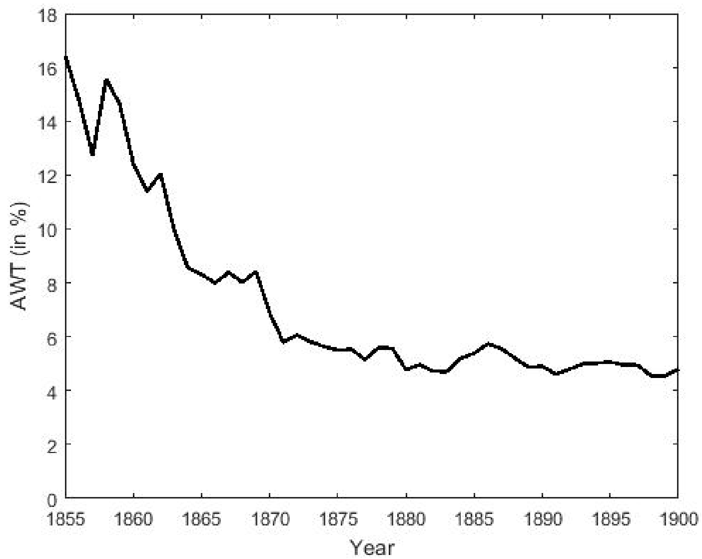
[50] Several examples of these tables extracted from official documents are shown in Appendix A.1.

[51] To calculate the values of imports and home consumption for 1840 and 1841, as McCloskey (1980) suggests, I mainly rely on the price estimates of Gayer et al. (1953). Other sources I use to obtain current prices are Smith (1841) and Tooke (1848).

[52] As can be seen in the sample pages in Appendix A.1, current values are reported as "computed real value".

[53] According to the Report of the Select Committee of the House of Commons on Import Duties printed in August 1840, there were 862 articles in the tariff schedule of 1839. The number of varieties presented on Table 1.1 for the years 1840 and 1841 differ from the number of articles in the tariff schedule, this is partly due to availability of data for articles that produced less than 100 pounds of duty and partly due to the aggregation I had to do since prices for these years are mostly available as averages. For example, import duties on sugar differed based on the exporting country and the type of sugar imported, but annual prices are available for raw sugar, refined sugar, cane juice and molasses, so I aggregated sugar imports according to the classification dictated by the average prices. Similarly, until 1860 when all tariffs on wood were reduced to a single rate of 1s. per ton, there were 52 different rates of duty on wood determined based on the location of growth and produce, thickness, length and breadth, but while they listed all different rates of duty, official documents provide net receipt of customs duty with some level of aggregation. British Parliamentary Papers (1898) provides the tariff schedules from 1800 to 1897. While the number of articles differ from the tariff schedule, data covers the whole tariff revenue for these years. In both 1840 and 1841, seventeen main articles (sugar, tea, tobacco, spirits, wine, timber, corn and meal, coffee, butter, currants, tallow, seeds, raisins, cheese, cotton wool, sheep's wool and silk manufactures) produce 94.5 percent of the total tariff revenue. Missing or unreadable statistics until 1897 were collected from parliamentary papers.

Figure 1.1: Average Weighted Tariffs of Britain 1855-1900



stable in nominal terms throughout the covered period. Using these figures, I calculate the tariff rates on individual products which are then aggregated to obtain the industry-level average weighted tariffs (AWT).[54] The declining trend in AWT is illustrated in Figure 1.1. It increased 2 percent from 1957 to 1958 even though there was little change in the rate of import tariffs, this is mainly due to an increase in the imports of goods with high tariff rates like textile and food products. The AWT stayed almost constant after 1870 as is clearly visible on Figure 1.1.

Tables 1.2 and 1.3 show the export and import shares of main industries Britain traded in. Textiles, especially woollen goods, had historically been the main export of Britain but the developments during the industrial revolution brought substantial improvements in the production technology and with the cultivation of cotton in the colonies, Britain

[54] I adopt the industry classification suggested by Horrell et al. (1994) to match their input-output data for 1841. The classification they adopt is suitable for representing the structure of the British economy in the nineteenth century, for example, historically, dyes, candles and soaps were important articles which were widely consumed as final outputs by final consumers and as inputs in other industries like textiles production. Similarly, contrary to contemporary industry classifications, bricks, pottery and glass were important articles both commonly exported and used as inputs to other industries. Horrell et al. (1994) adopt them as separate industries to emphasize these relationships in their input-output table.

Table 1.1: Data Overview

Year	Number of Varieties	GDP	Imports	Duty	Year	Number of Varieties	GDP	Imports	Duty
1840	292	603	84	21	1877	355	1303	394	20
1841	214	588	85	24	1878	355	1278	369	20
1855	507	788	144	23	1879	355	1230	363	20
1856	510	825	172	24	1880	359	1313	414	19
1857	940	820	188	23	1881	359	1332	397	19
1858	943	787	165	24	1882	338	1371	419	19
1859	940	837	178	25	1883	338	1377	427	20
1860	918	860	211	23	1884	340	1338	390	20
1861	780	887	216	24	1885	341	1309	380	20
1862	777	892	225	24	1886	345	1317	357	20
1863	787	966	249	24	1887	348	1368	362	19
1864	787	1013	275	22	1888	349	1419	388	20
1865	787	1025	272	22	1889	362	1492	425	19
1866	791	1058	294	22	1890	367	1527	412	20
1867	787	1050	275	22	1891	372	1530	436	20
1868	784	1060	291	22	1892	381	1494	424	21
1869	778	1086	295	22	1893	386	1493	402	20
1870	776	1157	303	20	1894	386	1570	408	20
1871	353	1240	361	20	1895	389	1605	417	21
1872	351	1309	354	21	1896	395	1656	441	22
1873	353	1368	371	21	1897	398	1697	451	22
1874	354	1364	370	19	1898	400	1787	470	21
1875	352	1335	374	20	1899	407	1892	485	22
1876	355	1318	375	20	1900	435	1966	523	25

Note: The import, duty and GDP figures are in nominal millions of pounds. Collected from official statistics.

diversified the types of textiles it produced and maintained its command in world trade in the nineteenth century. Powerful machinery invented before the move to free trade was used to fuel the production and eventually the exports of other industries while exports of engines and machines were not allowed to keep this advantage at home. The rise in the export share of metal goods as seen in Table 1.2 partly came after the government revoked this ban and also Britain's lead in steel technology, which began to be cheaply and commonly produced in the 1860s, resulted in the British producers supplying a larger portion of the world demand than before. Britain was an importer of raw agricultural materials like cotton, flax and silk and also 'exotic' goods like sugar, rum, coffee and tobacco.[55]

Table 1.2: Export Shares (in %)

Industry	1841	1870
Agriculture	1.34	2.18
Mining and quarrying	1.65	3.41
Food, drinks and tobacco	2.43	4.18
Metal manufacture	9.16	7.87
Soap, candles and dyes	1.02	0.64
Textiles clothing and leather goods	71.78	62.66
Metal goods	5.64	13.92
Bricks, pottery and glass	1.40	1.57
Other manufacturing	5.58	3.57

Note: Displays the share of each industry in total exports for 1841 and 1870. Each column sums up to 100 percent. For sources, see text.

[55]Tobacco had been grown in Britain for centuries and was not exactly an 'exotic' good (MacInnes, 2013, p. 75), but since tobacco was one of the main products of the plantations, planting it in England and Ireland was reducing the crown's revenues, therefore all tobacco plantations were ordered to be destroyed and cultivation was banned in England by the act 12th Charles II 1660, c.34 and in Ireland by 1st & 2nd William IV 1831, c.13. Raw tobacco was imported into Britain from the colonies and manufactured in the country.

Table 1.3: Import Shares (in %)

Industry	1841	1870
Agriculture	43.27	47.97
Mining and quarrying	0.64	2.57
Food, drinks and tobacco	32.81	23.96
Metal manufacture	0.30	2.43
Soap, candles and dyes	2.91	2.67
Textiles clothing and leather goods	12.09	13.12
Metal goods	0.01	0.07
Bricks, pottery and glass	1.16	0.44
Other manufacturing	6.81	6.76

Note: Displays the share of each industry in total imports for 1841 and 1870. Each column sums up to 100 percent. For sources, see text.

British officials regularly collected statistics on the foreign trade and tariffs of other countries. I use the Statements Relating to Foreign Countries Compiled from the Official Returns of the Respective Countries published as supplements to the Tables of Revenue, Population and Commerce of the United Kingdom; Commercial Tariffs and Regulations, Resources, and Trade of the Several States of Europe and America; the Reports of the Commissioners of Her Majesty's Customs on the Customs; and the Return of the Rates of Import Duty Levied by the Existing Tariffs of European Countries and of the United States so far as Relates to the Principal Articles of the Produce and Manufacture of the United Kingdom to obtain bilateral tariffs imposed by the United States and France.[56] After calculating the AWT from these figures, I aggregate them up to seventeen industries and calculate the bilateral tariffs imposed by these countries to imports from Britain in 1841 and 1870. Figure 1.4 presents the change in tariffs. Due to limited availability of comparable data for 1841, I assume that the rest of the world is represented by these two countries. Although it is a restricting assumption, France and the United States were two of the main trading partners of Britain during the nineteenth century and together they

[56]I also benefit from Dayton (1842), Macgregor (1846), Macgregor (1847), Ogden (1869), and Bureau of Statistics (1872) to obtain data on the United States. Tariff line-level import duties for France in 1841 are available in British Parliamentary Papers (1842, p. 71)

provide an approximation of the average world tariff in 1870. Using data on 11 commodities and 41 countries, Tena-Junguito et al. (2012) calculate the AWT on manufacturing trade in the world in 1870 as 21 percent, while according to the data presented here, the AWT in manufacturing goods was 26 percent in 1870 for France and the United States combined. The United States was the main trading partner of Britain for most of the nineteenth century, in 1841 exports to the United States made up almost 15 percent and in 1870, 21 percent of total British exports. In the first half of the nineteenth century, the commercial policy of the United States was based on the principle of "creating, maintaining and protecting domestic manufactures" (Macgregor, 1847, p. 1314), in order to achieve this, the countervailing tariffs imposed on British imports in 1789 were followed by the protective tariffs of 1816.[57] Modifications were later made in the tariff schedule and by 1832, tariffs reached 42 percent on cotton goods, 54 percent on certain types of woollen goods, and 95 percent on iron goods. By the Compromise Act of 1832, it was agreed by the United States government to gradually reduce these tariffs to 20 percent by 1842 and eliminate tariffs on many other articles (Macgregor, 1846, p. 1415). The tariffs were increased again however, in the 1860s, primarily to finance the Civil War and no revisions were made after the war ended (Hawke, 1975). Slight reductions were made in 1883 which were later reversed by the consecutive acts passed in the 1890s.[58] As Irwin (2001) states, during the last 30 years of the nineteenth century, the United States was a protectionist country with its tariffs at historic highs. France was also a significant trading partner of Britain, the share of exports to this country rose from 5 percent to 15 percent from 1841 to 1870. Although French physiocrats like Turgot and Quesnay were early contributors to the development of the idea of free trade in the eighteenth century and liberal theories of commercial policy received prominence in France

[57]As Macgregor (1847) notes, although the preambles of early acts of the United States declared the principle of protection, the average duty on British manufactured goods were not more than 10 percent until the nineteenth century and were more for raising revenue than restricting British imports. A detailed account of the early commercial policy of the United States is given in Hill (1893). The act of 1816 imposed high tariffs on main exports of Britain, for example there was a 30 percent tariff on all manufactures of leather, a 25 percent tariff on all woollen goods, and a 20 percent tariff on cotton goods.

[58]The McKinley Act of 1890, the Wilson-Gorman Act of 1894, and the Dingley Act of 1897.

around the same time as England, imports into France remained subject to prohibitions, blockades and high tariffs during the early decades of the nineteenth century.[59] As in the United States, French industrialists sought the protection of manufacturing industries when the restoration of peace in 1815 after the Napoleonic wars brought the resumption of trade with England. While industrialists in Britain formed the Anti-Corn Law League to lobby for trade liberalization, French industrialists created the Comité pour la Défense du Travail National (*Association for the Defence of National Labour*) to defend protection (Noël, 1879, p. 85). The protection of manufactured products remained as a feature of the commercial policy of France until the end of 1840s. A sliding scale of import duties on foreign grain similar to the one in England was also in force from 1819 until 1861 (Haight, 1941, p. 19). In 1860, a commercial treaty between Britain and France, known as the Cobden-Chevalier Treaty, was signed. Accordingly, France abolished all prohibitions and agreed that the import tariffs should not exceed 30 percent ad valorem, this limit was later reduced to 25 percent in 1864 (Bairoch and Burke, 1989). In return, with the budget of 1860, Britain reduced the import tariff on wine by 70 percent. During a period when the import tariffs in the United States went up, Cobden-Chevalier reinforced the move to free trade in Europe for the following ten years, before the protectionist ideas gained momentum once again in late 1870s (Tena-Junguito et al., 2012). By 1870, France had moderate tariffs on manufactured goods around 10 percent and free imports in almost all raw materials and food.

I use the input-output table constructed by Horrell et al. (1994) to incorporate the interrelationships among industries in the model presented in section 1.4. They provide an input-output table for Britain in 1841. Unfortunately, I don't have a similar table for France or the United States and have to assume the same relationship among industries for the whole sample.[60] Using the industry classification suggested by Horrell et al. (1994), a

[59]See Irwin (1998) for details on the international trade doctrine of the physiocrats.

[60]Other historical input-output tables in the literature are Thomas (1984) for Britain in 1907, Whitney (1968) for the United States in 1899 and Bohlin (2007) for Sweden in 1885, 1898 and 1913.

Table 1.4: Average Import Tariffs, 1841 vs 1870 (in %)

Industry	Britain 1841	Britain 1870	RoW 1841	RoW 1870
Agriculture	16.55	0	18.00	26.87
Mining and quarrying	19.57	0	18.48	25.28
Food, drinks and tobacco	77.94	58.12	20.01	20.76
Metal manufacture	16.68	0	22.20	24.92
Soap, candles and dyes	4.23	0	19.00	36.15
Textiles, clothing and leather goods	3.92	0	23.04	39.22
Metal goods	27.40	0	16.03	21.87
Bricks, pottery and glass	3.10	0	20.00	39.72
Other manufacturing	4.13	0	21.10	22.94
Construction	0	0	0	0
Gas and water	0	0	0	0
Transport	0	0	0	0
Distribution	0	0	0	0
Domestic service	0	0	0	0
Other service	0	0	0	0
Public administration and defence	0	0	0	0
Housing services	0	0	0	0

Note: Displays average import tariffs in Britain and the rest of the world (RoW) in 1841 and 1870. RoW is represented by the United States and France. For sources, see text.

more detailed look into the structure of import tariffs reveals that before the move to free trade the effect of protection in Britain was primarily felt in the food industry and raw materials. As shown in table 1.4, the tariff on agricultural goods was 17 percent, mining goods was 20 percent. Tariffs on food, drinks and tobacco was almost 78 percent. In the height of the industrial revolution, Britain became an important exporter of metal goods like anchors, grapnels, hoops and nails; and metal manufactures, which were used as inputs in the production of metal goods, like unwrought metals, pig iron and iron bars. Tariffs on imports of both industries were kept high to protect these industries. By 1870, Britain had already eliminated all of its protective import tariffs and the customs revenue was primarily raised through tariffs on spirits, sugar, tea and tobacco. Tariffs on imports from Britain increased on average primarily due to the high share of the United States as a trading partner in British exports. The next section describes the model I use to evaluate the impact of these changes in tariff schedules on the British economy.

1.4 The Trade Model

Section 1.2 documents the history of Britain's move to free trade in the nineteenth century and section 1.3 presents the changes in British import tariffs and the tariffs levied on British exports from the period just before this move had started up to 1870 when many protectionist tariffs had been abolished in Britain. To measure the general equilibrium welfare effects of these changes in international trade policy, I use a gravity model in the vein of Caliendo and Parro (2015). I employ this particular general equilibrium trade model because it accommodates all features of the data like multiple countries, multiple industries, tradable intermediate goods, and a comprehensive input-output structure. Despite these rich features, the model offers a very tractable and quantifiable theoretical framework for evaluating trade policy.

1.4.1 Environment

The world consists of a number of countries indexed by $n, i, h \in \{1, ..., N\}$. A representative consumer in each country inelastically supplies L_n units of labour to the production of $j \in \{1, ..., J\}$ industries. The representative consumer derives utility from a final consumption good defined as a Cobb-Douglas aggregate of industry-specific final consumption goods:

$$U_n = \prod_{j=1}^{J} C_n^{j\,\alpha_n^j} \tag{1.1}$$

where α_n^j is the expenditure share on industry j goods and $\sum_{j=1}^{J} \alpha_n^j = 1$.

These non-tradable industry-specific final goods are produced from tradable intermediate goods by perfectly competitive firms according to a constant elasticity of substitution (CES) production technology:

$$Q_n^j = \left[\int_0^1 q_n^j(\omega)^{1-1/\sigma^j} d\omega \right]^{\sigma^j/(\sigma^j-1)} \tag{1.2}$$

where Q_n^j is the output of a non-tradable final consumption good, $q_n^j(\omega)$ is the quantity of the tradable intermediate good of variety ω, and σ^j is the elasticity of substitution across intermediate goods in industry j. The final goods Q_n^j can be directly consumed or used as materials in the production of intermediate goods $q_n^j(\omega)$.

In each industry, a continuum of tradable intermediate goods $\omega \in (0, 1)$ is produced with labour and materials following a constant returns to scale technology under perfect competition:

$$q_n^j(\omega) = z_n^j(\omega)\ l_n^j(\omega)^{\gamma_n^j} \prod_{k=1}^{J} m_n^{k,j}(\omega)^{\gamma_n^{k,j}} \tag{1.3}$$

where $l_n^j(\omega)$ is labour, $m_n^{k,j}(\omega)$ is the demand for final goods from industry k used in the production of intermediate good ω in industry j, and $z_n^j(\omega)$ is the efficiency of producing good ω in industry j and country n.[61] Labour is mobile across industries but not mobile across countries. $\gamma_n^j \geqslant 0$ is the share of value-added in industry j, and $\gamma_n^{k,j} \geqslant 0$ is the share of final goods from industry k used in the production of ω in industry j. Production of intermediate goods are constant returns to scale, so $\sum_{k=1}^{J} \gamma_n^{k,j} + \gamma_n^j = 1$.

A perfectly competitive market structure and constant returns to scale imply that the cost of an input bundle for producing good ω is given by

$$c_n^j = \Upsilon_n^j \; w_n^{\gamma_n^j} \; \prod_{k=1}^{J} P_n^k \; {}^{\gamma_n^{k,j}} \tag{1.4}$$

where w_n is the wage earned by labour in country n, P_n^k is the price of a final good from industry k and $\Upsilon_n^j = \prod_{k=1}^{J} (\gamma_n^{k,j})^{-\gamma_n^{k,j}} (\gamma_n^j)^{-\gamma_n^j}$.

Intermediate goods are tradable and trade is costly. Shipping intermediate goods from country i to country $n \neq i$ incurs iceberg trade costs and an ad valorem tariff. For each unit of a given product in industry j that arrives in country n, $d_{ni}^j \geqslant 1$ units must be exported from country i. There is no trade cost within a country, $d_{nn}^j = 1$. For goods imported by country n from country i, an ad valorem tariff, $\tau_{ni}^j \geqslant 0$ must be paid. Combining both, total trade costs on imports of country n from country i are represented by $t_{ni}^j = d_{ni}^j(1 + \tau_{ni}^j)$. intermediate goods are imported from the cheapest source considering trade costs, input costs and technology. The unit price of an intermediate good produced in country i and exported to country n is then equal to:

$$p_n^j(\omega) = \min_i \left\{ \frac{c_i^j t_{ni}^j}{z_i^j(\omega)} \right\} \tag{1.5}$$

[61]Following Eaton and Kortum (2002), the productivity level in producing good ω in industry j and region n, $z_n^j(\omega)$, is drawn from a Fréchet distribution with CDF $F_n^j(z) = e^{-T_n^j z^{-\theta^j}}$. Firms in industry j differ in terms their productivity levels, therefore price differences across goods ω arise from differences in productivity.

and the corresponding unit price for the final good in industry k in country n is

$$P_n^j = \left[\int_0^1 p_n^j(\omega)^{1-\sigma^j} d\omega \right]^{1/(1-\sigma^j)} \tag{1.6}$$

Given the assumptions on the productivity distribution, price of a final good in industry j can be obtained as

$$P_n^j = \eta^j \left[\sum_{i=1}^N T_i^j \ (c_i^j t_{ni}^j)^{-\theta^j} \right]^{-1/\theta^j} \tag{1.7}$$

where η^j is a constant.

Given Cobb-Douglas preferences, the consumption price index in country n is

$$P_n = \prod_{j=1}^J (P_n^j / \alpha_n^j)^{\alpha_n^j} \tag{1.8}$$

Total expenditure in country n on industry j goods is $X_n^j = P_n^j Q_n^j$. Total expenditure of country n on industry j goods from country i is X_{ni}^j. Therefore, the share of expenditure in country n on goods from country j can be written as $\pi_{ni}^j = X_{ni}^j / X_n^j$. Using the properties of the productivity distribution, the expenditure share of country n on industry j goods can be expressed in terms of bilateral trade costs, costs of the input bundle, and technologies:

$$\pi_{ni}^j = \frac{T_i^j \left[c_i^j t_{ni}^j \right]^{-\theta^j}}{\sum_{h=1}^N T_h^j \left[c_h^j t_{nh}^j \right]^{-\theta^j}} \tag{1.9}$$

1.4.2 Equilibrium

Goods market clear in the competitive equilibrium, therefore total final good available in country n and industry j is equal to the demand by the representative consumer and the intermediate goods producers, $Q_n^j = C_n^j + \sum_{k=1}^J \int_0^1 m_n^{j,k}(\omega) \ d\omega$. Then, the total expenditure on industry j goods is the sum of expenditures on final goods by firms and the representative consumer and is given by

$$X_n^j = \sum_{k=1}^{J} \gamma_n^{j,k} \sum_{i=1}^{N} X_i^k \frac{\pi_{in}^k}{1+\tau_{in}^k} + \alpha_n^j I_n \tag{1.10}$$

where total income in country n is the sum of labour income, tariff revenue and trade deficit:

$$I_n = w_n L_n + \sum_{j=1}^{J} \sum_{i=1}^{N} \tau_{ni}^j X_n^j \frac{\pi_{in}^j}{1+\tau_{in}^j} + D_n \tag{1.11}$$

Total deficits across countries is zero, $\sum_{n=1}^{N} D_n = 0$. National deficits are the sum of industry-level deficits, $D_n = \sum_{j=1}^{J} D_n^j$ where industry-level deficits are defined by the difference between imports and exports:

$$D_n^j = \sum_{i=1}^{N} X_n^j \frac{\pi_{ni}^j}{1+\tau_{ni}^j} - \sum_{i=1}^{N} X_i^j \frac{\pi_{in}^j}{1+\tau_{in}^j} \tag{1.12}$$

Finally, summing equation (1.12) over all industries yields the trade balance condition:[62]

$$D_n = \sum_{j=1}^{J} \sum_{i=1}^{N} X_n^j \frac{\pi_{ni}^j}{1+\tau_{ni}^j} - \sum_{j=1}^{J} \sum_{i=1}^{N} X_i^j \frac{\pi_{in}^j}{1+\tau_{in}^j} \tag{1.13}$$

Definition 1.1. An equilibrium is a set of wages $\{w_n\}$ and prices $\{P_n^j\}$ such that given L_n, T_n^j, τ_{ni}^j, d_{ni}^j, and D_n, equations (1.4), (1.7), (1.9), (1.10), (1.11), and (1.13) hold for all n, j.

1.4.3 Equilibrium for given tariff changes

Before performing the counterfactual exercises, in this section I obtain the counterfactual equilibrium in relative changes following the methodology of Dekle et al. (2008) for easy calibration and analysis. This approach allows me to solve the model without estimating or assuming the parameters like total factor productivity and transport costs that are already embedded in the initial equilibrium and do not change in the counterfactual equilibria. Let

[62] In the model, national trade deficits are exogenous but industry-level deficits are endogenously determined.

x' denote the value of variable x after the change in policy and $\hat{x} = \frac{x'}{x}$ denote the relative change in x due to policy. Applying this formulation, the model can be expressed in terms of relative changes. From equations (1.4) and (1.7), relative changes in unit costs and prices are

$$\hat{c}_n^j = \hat{w}_n^{\gamma_n^j} \prod_{k=1}^{J} \hat{P}_n^{k\ \gamma_n^{k,j}} \tag{1.14}$$

$$\hat{P}_n^j = \left[\sum_{i=1}^{N} \pi_{ni}^j [\hat{t_{ni}^j} \hat{c}_i^j]^{-\theta^j} \right]^{-1/\theta^j} \tag{1.15}$$

Using these two expressions and the exogenous change in tariffs, the relative change in trade shares can be obtained as

$$\hat{\pi}_{ni}^j = \left[\frac{\hat{t}_{ni}^j \hat{c}_i^j}{\hat{P}_n^j} \right]^{-\theta^j} \tag{1.16}$$

From equations (1.10) and (1.16), the counterfactual expenditures after the policy is imposed becomes

$$X_n^{j\prime} = \sum_{k=1}^{J} \gamma_n^{j,k} \sum_{i=1}^{N} \frac{\pi_{in}^{k\ \prime}}{1 + \tau_{in}^{k\ \prime}} X_i^{k\prime} + \alpha_n^j I_n' \tag{1.17}$$

where the counterfactual level of income is

$$I_n{}' = w_n{}' L_n + \sum_{j=1}^{J} \sum_{i=1}^{N} \tau_{ni}^{j\ \prime} \frac{\pi_{ni}^{j\ \prime}}{1 + \tau_{ni}^{j\ \prime}} X_n^{j\prime} + D_n \tag{1.18}$$

Finally, following equation (1.13), the trade balance in the counterfactual equilibrium satisfies

$$D_n = \sum_{j=1}^{J} \sum_{i=1}^{N} X_n^{j\prime} \frac{\pi_{ni}^{j\ \prime}}{1 + \tau_{ni}^{j\ \prime}} - \sum_{j=1}^{J} \sum_{i=1}^{N} X_i^{j\prime} \frac{\pi_{in}^{j\ \prime}}{1 + \tau_{in}^{j\ \prime}} \tag{1.19}$$

The objective of this system of equations is to evaluate the general equilibrium effects of an exogenous change in trade policy on welfare. Given these counterfactual equilibrium conditions, initial bilateral trade shares, π_{ni}^j, and parameters, α_n^j, γ_n^j, $\gamma_n^{k,j}$, θ^j, τ_{ni}^j, $\tau_{ni}^{j\ \prime}$ obtained from data, the model can be solved through an algorithm. From an initial guess of wage changes $\hat{w} = (\hat{w}_1, ..., \hat{w}_n)$, I first solve for equilibrium input costs, $\hat{c}_n^j$, and prices, $\hat{P}_n^j$, from equations (1.14) and (1.15). Counterfactual bilateral trade shares, ${\pi_{ni}^j}'$, can then be calculated. Holding initial aggregate trade deficits, D_n, constant, counterfactual expenditures, $X_n^{j\prime}$, are calculated using equation (1.17). The last step is to verify if the trade balance condition given in equation (1.19) holds. If not, the vector of wage changes is adjusted and the process is repeated until the correct vector $\hat{w}$ that satisfies the trade balance condition is found. The following section describes the corresponding welfare equation and provides a decomposition of the welfare effects into terms of trade and volume of trade effects that I use for quantitative assessment in section 1.5.

1.4.4 Welfare effects of tariff changes

Income of the representative consumer is determined by the lump sum tariff revenue, wages and trade deficit, therefore welfare of a representative consumer in country n is equivalent to the real income, $W_n = I_n/P_n$ where I_n is given by equation (1.11) and P_n is given by equation (1.8).

The relative changes in income and the price index substituted in the following expression yield the equilibrium change in welfare following a change in policy:

$$\hat{W}_n = \frac{\hat{I}_n}{\hat{P}_n} \tag{1.20}$$

Following Caliendo and Parro (2015), the change in welfare can be decomposed into the terms of trade effect and the volume of trade effect from tariff changes, holding the iceberg trade costs constant. Totally differentiating W_n and using the equilibrium conditions given in section 1.4.2, the change in welfare becomes

$$d\ln W_n = \frac{1}{I_n}\sum_{j=1}^{J}\sum_{i=1}^{N}\underbrace{\left(E_{ni}^j d\ln c_n^j - M_{ni}^j d\ln c_i^j\right)}_{\text{terms of trade}} + \frac{1}{I_n}\sum_{j=1}^{J}\sum_{i=1}^{N}\underbrace{\tau_{ni}^j M_{ni}^j\left(d\ln M_{ni}^j - d\ln c_i^j\right)}_{\text{volume of trade}} \tag{1.21}$$

where $E_{ni}^j = X_i^j \frac{\pi_{in}^j}{1+\tau_{in}^j}$ are country n's exports to country i of industry j goods, and $M_{ni}^j = X_n^j \frac{\pi_{ni}^j}{1+\tau_{ni}^j}$ are country n's imports from country i of industry j goods. The terms of trade of a country is the ratio of exporter prices to importer prices, hence it measures the purchasing power of a country. Terms of trade effects from tariff changes can be quantified from the relative change in the price of exports and imports. When country n is a net exporter in industry j, a larger increase in the export price relative to the import price of industry j goods improves the terms of trade. And an improvement in terms of trade means country n can import more for a given unit of exports, therefore welfare increases. The second term in equation (1.21) measures the contribution of changes in the volume of trade to the change in welfare. The volume of trade effect is determined by the change in imports weighted by the change in import prices and its strength depends on the initial levels of imports and tariffs.

Total changes in terms of trade and volume of trade can be further decomposed across industries to obtain the contribution of each industry to the aggregate change in welfare. The change in terms of trade at the industry level is

$$d \ln ToT_n^j = \sum_{i=1}^{N} \left(E_{ni}^j d \ln c_n^j - M_{ni}^j d \ln c_i^j \right) \tag{1.22}$$

and the change in volume of trade at the industry level is simply

$$d \ln VoT_n^j = \sum_{i=1}^{N} \tau_{ni}^j M_{ni}^j \left(d \ln M_{ni}^j - d \ln c_i^j \right) \tag{1.23}$$

1.5 Quantifying Trade and Welfare Effects from Britain's Move to Free Trade

In this section, employing the model presented in section 1.4, I measure the trade and welfare effects of the change in tariff structure caused by Britain's move to free trade. The base year of evaluation is 1841, one year before the budget of 1842 which paved the way for the repeal of Corn Laws and Navigation Acts and reduced or abolished an extensive list of import tariffs. The counterfactual set of tariffs are from 1870 when Britain had eliminated a large portion of its protective import tariffs.

To assess the effect of changes in trade policy, I need to obtain the values of industry specific tariff rates, bilateral trade flows, value-added, and gross output. From these and the input-output table for 1841, I can calculate bilateral trade shares, trade deficits, value-added shares, shares of intermediate consumption, and expenditure shares. I also need the values of industry specific trade elasticity parameters. Apart from the tariff data presented in section 1.3, the counterfactual exercise requires data on the gross output, value-added shares, and expenditure shares. Industrial output and value-added data for Britain come from Horrell et al. (1994). There is no nominal output data available for the world in 1841. Maddison (1995) provides country-level output data in Geary-Khamis international dollars. Therefore, for the RoW, I calculate the nominal value of gross output by subtracting Britain's output from world output using the nominal British output data provided in Horrell et al. (1994). I assume the input-output structure and value-added shares to be common across both regions due to data availability. Among the seventeen industries listed on Table 1.4, Britain traded in the first nine. The model doesn't distinguish between tradable and non-tradable industries but by setting the trade costs for non-tradable industries as $d_{ni}^j = \infty$, I assume it is always cheaper to source these goods from local suppliers in both regions.

I calculate the industry specific expenditure shares, α_n^j, as the share of the gross value of domestic production net of industry specific trade deficits and the intermediate goods expenditure in total income. Finally, I need the industry specific import demand elasticities. Stern et al. (1976) compile disaggregated import demand elasticities from various studies estimated for periods from 1950s to 1970s. I rely on their "best" elasticity estimates since they match up with the industry categories I adopt.

Table 1.5: Home Shares and Expenditure Shares in Britain, by Industry

Industry	π_{nn}^{j}	α_{n}^{j}
Agriculture	82.35	0.1643
Mining and quarrying	96.29	0.0116
Food, drinks and tobacco	87.23	0.2696
Metal manufacture	97.56	0.0036
Soap, candles and dyes	80.33	0.0171
Textiles, clothing and leather goods	89.36	0.1248
Metal goods	99.96	0.0146
Bricks, pottery and glass	83.49	0.0044
Other manufacturing	75.94	0.0343

Note: Displays home shares and expenditure shares for tradable industries in the baseline equilibrium. Home shares, π_{nn}^{j}, are in percentages.

Table 1.5 shows the home consumption shares and expenditure shares for Britain from the calibrated model for 1841. As indicated by the high home consumption shares, British market in general had a low import penetration. High home consumption shares however should be expected for the period before the start of the rapid growth in commercial integration during the "first era of globalization" in the 1870s. The lowest home consumption share is in other manufacturing which includes furniture made of wood indigenous to Caribbean and South America like lignum vitae and brazilwood, and speciality goods like musical instruments and clocks generally imported from Europe. Chemical dyes used in textile manufacturing not produced in Britain like madder root and indigo make a large share of the imports in soaps, candles and dyes. Another relatively low home consumption share is in the agriculture. Due to unfavourable climate, certain agricultural products like rice, some kinds of fruits and seeds were not produced in Britain and were mainly imported. Bricks, pottery and glass has a home share of 83.5 percent, although bricks were mainly produced at home, porcelain and certain glass products were imported. As it should be typical for the economies in the early nineteenth century, among these industries, the highest final expenditure shares are in food, drinks and tobacco, agriculture and textiles.

Table 1.6: Welfare Effects from Britain's Tariff Reductions

	Terms of Trade	Volume of Trade	Total
Britain	-0.11%	0.91%	0.80%
RoW	0.33%	0.09%	0.42%

I analyse the welfare effects of tariff changes under two scenarios. The first scenario assumes a unilateral tariff reduction in Britain and no change in import tariffs in the RoW. And under the second scenario, I analyse the effect from the increase in import tariffs in the RoW as described in Table 1.4. The change in welfare under the first scenario is reported in Table 1.6. The unilateral tariff reduction by Britain raises its welfare by 0.80 percent. Decomposing this total change in welfare shows that the source of increase is the gains from trade creation with 0.91 percent while the welfare loss from the change in terms of trade is 0.11 percent. Although the magnitudes are small, the welfare increases in both regions. This contradicts with the results of Harley and McCloskey (2002), McCloskey (1980), and Irwin (1988) who argue that Britain's welfare declined between 2 to 6 percent as a result of the trade liberalization in 1840s. Irwin (1988) analyses the change in terms of trade and finds an adverse shift on the order of 2 percent. The change in terms of trade can be understood by looking into how export and import prices change in response to a unilateral tariff reduction. From equation (1.14), export prices rise with wages and the costs of intermediate inputs. Real wages increase in Britain by 0.27 percent. And, from equation (1.15), all else equal, costs of intermediate inputs decrease with reductions in tariffs. Therefore, the net effect on export prices depends on the relative magnitudes of these two forces. On average, Britain's export prices decrease. All else equal, due to the decrease in the cost of imports from Britain, cost of intermediate inputs decrease in the RoW, but the importer prices increase since the change in wages dominates the decrease in the cost of intermediate inputs.

Input-output linkages between industries create a multiplicative effect on the magnitude of the terms of trade change at the industry level and this in turn determines the contribution of each industry to the change in total terms of trade. This can be seen from the figures presented on Table 1.7 which displays the contribution of each industry to the change in welfare.[63]

The change in the terms of trade of Britain can be explained mainly by three industries. Food, drinks and tobacco industry accounts for 11.81 percent of the change in terms of trade. The import tariffs applied on the industry are not totally abolished but the share of intermediate inputs used in the production of food, drinks and tobacco is 78 percent, which is larger than the average 36 percent across all industries. Approximately two thirds of intermediate inputs used in this industry come from agriculture and the change in the terms of trade in agriculture aggravates the terms of trade change in this industry. Another example is textiles, the primary export of Britain. The decrease in import tariffs on textiles is low compared to other industries (3.92 percent) but textiles industry sources its intermediate inputs mainly from imported materials including agriculture. Main imports of Britain, agriculture and food, drinks and tobacco, as shown in Table 1.3, account for more than two thirds of the increase in Britain's volume of trade. The magnitude of the reduction in tariffs, the trade elasticity and the share of intermediate inputs used in production affect the magnitude of the change in volume of trade.

The relative contribution of each industry to the aggregate change in volume of trade also depends on initial tariffs and imports. Agriculture is an industry with relatively homogeneous output for the period, therefore even small changes in tariffs on the imports of the industry has a large effect on the volume of trade. Also it is Britain's main import. These in

[63]The values on Table 1.7 and 1.9 are calculated for each industry j as $d\ln ToT_n^j / \sum_{j=1}^{J} d\ln ToT_n^j$ and $d\ln VoT_n^j / \sum_{j=1}^{J} d\ln VoT_n^j$ under the two scenarios.

turn affects the trade in industries that use its output like food, drinks and tobacco and textiles industries. During the nineteenth century, with the growth of its manufacturing industries, Britain became a net importer of raw materials and semi-manufactured goods and an exporter of manufactured goods. Therefore, as the import tariffs are reduced, the effect of changes in the cost of intermediate inputs are easily spread across all industries. Incorporating these links between industries allows me to demonstrate the total impact of the change in Britain's trade policy.

Table 1.7: Industrial Contribution to Welfare Effects After Britain's Tariff Reductions

Industry	Terms of Trade	Volume of Trade
Agriculture	16.57%	59.74%
Mining and quarrying	1.14%	4.61%
Food, drinks and tobacco	11.81%	19.73%
Metal manufacture	7.84%	0.70%
Soap, candles and dyes	4.60%	1.54%
Textiles, clothing and leather goods	50.00%	11.49%
Metal goods	3.45%	0.27%
Bricks, pottery and glass	2.21%	0.59%
Other manufacturing	2.38%	1.33%

Irwin (1988) argues incorporating the change in foreign tariffs in the analysis are "essential if we wish to judge whether or not Britain ultimately reaped benefits from free trade" during this period. In the second scenario, I demonstrate the effect of the change in bilateral tariffs imposed on imports from Britain. Table 1.4 presents the average foreign import tariffs for each industry. Mainly due to the changes in the tariff structure in the United States and the high shares of imports in Britain from this country, the bilateral tariffs in the RoW are higher in all industries in 1870. It is important to remember that the change in foreign tariffs is represented by the tariffs of United States and France due to data availability. From official reports to the parliament, we know that most of the trading partners of Britain, especially in

Europe, gradually moved to free trade later during the second half of the nineteenth century. Therefore, the figures presented here should be seen as a result of the largest possible set of import tariffs imposed on exports of Britain by the RoW during this period. The welfare effects of the tariff increase in the RoW are presented in Table 1.8.

Table 1.8: Welfare Effects from the Change in Tariff Structure of the RoW

	Terms of Trade	Volume of Trade	Total
Britain	-0.40%	-0.35%	-0.75%
RoW	0.15%	-0.06%	0.09%

There is a small decrease in volume of trade for both Britain and the RoW. Britain's exports decline in all industries. Table 1.9 shows the contribution of each industry to the change in volume of trade in Britain. Agriculture, food, drinks and tobacco and textiles are the main contributors to the loss of trade between Britain and the RoW.

Table 1.9: Industrial Contribution to Welfare Effects in Britain from the Change in Tariff Structure of the RoW

Industry	Terms of Trade	Volume of Trade
Agriculture	17.15%	23.28%
Mining and quarrying	1.15%	2.66%
Food, drinks and tobacco	12.37%	44.11%
Metal manufacture	7.76%	3.16%
Soap, candles and dyes	3.69%	0.37%
Textiles, clothing and leather goods	49.73%	22.55%
Metal goods	3.31%	1.01%
Bricks, pottery and glass	2.23%	1.11%
Other manufacturing	2.62%	1.76%

As shown in Table 1.8, the effect of the tariff increase in the RoW on Britain's welfare is negative but small. Even though the volume of trade effect is negative, the terms of trade effect is positive in the RoW and larger in magnitude. Analysing the terms of trade effect at the industry level explains the reason behind this negative outcome for Britain. In a model with intermediate goods, as shown in equation (1.22), terms of trade effects at the industry level depend on the changes in import and export prices and the trade deficit. Textiles industry by itself, contributes to 50 percent of the change in the terms of trade of Britain (see Table 1.9). It is the main export of the country with the value of total exports being 16 times larger than the imports at the initial equilibrium, therefore the impact of an increase in tariffs is large. From Table 1.9, main imports of Britain, agriculture and food, drinks and tobacco account for approximately 30 percent of the decrease in terms of trade. Britain has a trade deficit in both of these industries. Export prices depend on wage changes and the changes in the prices of intermediate inputs. In agriculture, share of value added is high (70 percent), and the share of imported intermediate inputs is low (0.13 percent). Therefore, the change in wages is an important determinant of the change in the price of agricultural goods. Wages decline in Britain at a larger magnitude than in the RoW. The share of intermediate inputs from the agriculture industry in food, drinks and tobacco is high (78 percent) and the change in the relative price of agricultural goods exacerbates the terms of trade effect in the industry.

The welfare implications of the tariffs are small and when the changes in the tariff structures of Britain and the RoW are fully accounted for, in total, the increase in the volume of trade as a result of Britain's trade liberalization dominates and the welfare increases by 0.05%. Therefore, even though it is by a small margin, Britain did not lose from the move to free trade. The negative welfare effect of the change in the tariff structure of the RoW can be seen as the largest possible decrease Britain's welfare endured during this period since other trade partners especially in Europe who were also going through a period of trade liberalization are not accounted for as a part of the RoW in this study due to data limitations.

1.6 Conclusion

Using a quantitative general equilibrium model, I examine the welfare implications of Britain's move to free trade in the nineteenth century. The effect of the unilateral move to free trade on welfare is positive and substantially lower in magnitude than previously calculated. Decomposing the aggregate effect into the terms of trade and volume of trade effects shows that Britain's repeal of protective import tariffs affected its welfare in line with the direction of change in volume of trade. The trade creation effect of the decrease in tariffs is about 1 percent. The results confirm that the nineteenth century policy makers were correct in predicting that eliminating tariffs on agriculture could improve workers' living standards by providing cheap food to the consumers even though there was a small decrease in real wages.[64]

The repeal leads to import prices of raw materials like agricultural goods to fall, these are the main materials used as inputs in manufacturing industries like textiles. Since Britain is an importer of raw and semi-manufactured goods and an exporter of manufactured goods during this period, the interrelations between industries play an important role in the final welfare outcome by creating a strong input-output feedback in the economy. Previous literature on the subject mostly assume a single industry environment and examine the effect of the decrease in average import tariffs.

The results of the second quantitative exercise show that even though welfare declines in Britain as a result of the change in the tariff structure of the RoW, the effect is not large enough to overpower the result of trade liberalization. The simulations imply that Britain's move to free trade in the nineteenth century improved its welfare by 0.80 percent, through the trade creation effect of lower tariffs. The direction of change in welfare holds

[64]According to O'Rourke (1997), this was not true for all countries in the nineteenth century, as a result of the cheaper imported food, most European countries suffered from large declines in real wages. This difference was probably because of the already low agricultural production and employment in Britain compared to continental economies.

after considering the possible increase in the tariffs imposed on imports from Britain.

Chapter 2

Pricing Carbon in Canada: An Analysis of Canada's Commitment under the Paris Agreement

2.1 Introduction

In 2016, the federal government ratified the Paris Agreement and Canada became one of the 185 countries pledged to limit the rise in average global temperatures to less than 2 degrees C above pre-industrial levels. According to the agreement, Canada's commitment is to reduce its carbon emissions by 30 percent below 2005 levels by 2030. Later in 2016, the government announced the Pan-Canadian Framework on Clean Growth and Climate Change. According to the framework, provincial and territorial governments implement either a cap-and-trade program or a carbon tax in line with the federal minimum price, or the federal government introduces an explicit price-based system in jurisdictions that do not adopt a form of carbon pricing. There is growing concern among some provincial governments about the potential negative impact of the federal carbon pricing scheme on welfare and industries that face competitiveness pressures.[1] Provinces and territories vary

[1] In an analysis published in 2018, Government of Saskatchewan expressed concern on the potential negative impact on the local industries, for this analysis see https://www.saskatchewan.ca/government/news-and-media/2018/june/27/fed-carbon-tax.

substantially in terms of their economic structures and emissions profiles. This raises the main questions I examine in this paper: What are the provincial trade and welfare effects of meeting Canada's commitment under the Paris Agreement? And what is the extent of emissions relocation out of Canada if the Paris Agreement targets are achieved? To answer these questions, I introduce carbon pricing to a multi-industry Ricardian model of trade with inter-industry linkages and investigate the trade and welfare effects of meeting the proposed federal benchmark standards on the Canadian economy at the provincial and national levels.

A common concern among provinces with unilaterally enforced carbon pricing is the competitiveness pressure on the so-called "emissions intensive and trade exposed" (EITE) industries. These are the vulnerable industries which may see their costs rise disproportionately compared to others and as a result, see their competitiveness erode. Differences in carbon prices across provinces and Canada's international trade with countries with less-stringent carbon policies are at the heart of the concern over domestic firms losing market share. I examine the effects of carbon pricing on production, interprovincial and international trade patterns, and welfare at the provincial level. It is important to examine the effects of carbon pricing at a regional level because the distribution of industry-level production is not uniform across Canada and different regions differ significantly in what they mainly produce, for example while mining makes up a big share of Alberta's GDP, services like wholesale and retail are the important contributors to Ontario's GDP. Emissions intensities and trade exposure also vary a lot at the provincial and industry levels. Therefore, as emphasized in this paper, economic geography is an important aspect that influences the degree of exposure to carbon pricing in Canada. Using a multi-industry trade model with input-output relationships, I identify the vulnerable industries in every province. Input-output relationships in the model allow me to assess every industry with its direct and indirect CO_2 emissions. Direct CO_2 emissions are a result of fossil fuels used during production and these are what most studies in the literature examine when they quantify the effects of carbon pricing.

However, industries are interrelated through input-output linkages and indirect emissions are also created by sourcing inputs from other industries. If indirect emissions are not taken into account, we may not be able to identify the most vulnerable industries to changes in carbon prices. An industry that is not emissions intensive on the basis of its energy use may still face the competitiveness pressures mentioned earlier as carbon prices increase if it uses emissions intensive inputs from other industries. This is relevant for the current policy discussion on carbon pricing as various design choices are available for provincial governments to manage these competitiveness risks but addressing the challenge primarily requires identifying the vulnerable industries accurately.

With concerns about competitiveness comes the problem of "carbon leakage". Through their effects on various inputs used in the production, carbon pricing may hinder the ability of domestic firms to compete in export markets since unilateral actions to restrict emissions changes the relative goods prices and eventually affect trade patterns. As the literature on carbon leakage suggests (Felder and Rutherford (1993), Aichele (2013), Aichele and Felbermayr (2015)), this effect on trade patterns may shift the emissions to regions with less stringent emission constraints and increase global emissions. Will emissions simply relocate out of Canada and stiffer carbon regulations become unfruitful? In this paper, I quantify the extent of carbon leakage in response to Canada's unilateral action to increase the cost of emissions as described in its Nationally Determined Contribution (NDC) under the Paris Agreement. The counterfactual exercises show that 10.8% of aggregate emissions relocate out of Canada but the leakage is reduced by 1.43% when the Output-Based Pricing System is taken into account. The analysis focuses on Canada's unilateral action to meet its commitment, therefore the extent of leakage will be even smaller if other countries' actions to limit their emissions as negotiated in the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) are also taken into account.

Several other studies have investigated the extent of carbon leakage and the heterogeneous effects of carbon pricing across regions in a similar framework. Aichele (2013) incorporates fossil fuel use to the production function of a single industry gravity model based on Anderson and Van Wincoop (2003) and examines the implications of the commitments under the Kyoto protocol for carbon leakage. She finds a leakage rate of 10% in response to an emission allowance price of 15 US$ in the European Union. Egger and Nigai (2012) employ a similar model based on Eaton and Kortum (2002) to study the implications of reducing emissions to the levels specified in the Copenhagen Accord for a set of OECD countries. They find a leakage rate of 0.07% out of the OECD countries. In their single factor model with multiple industries, they assume that the mining and quarrying industry is the source of emissions and find that different welfare effects across countries primarily depend on the change in output from this polluting industry. By extending the gravity model based on Anderson and Van Wincoop (2003) to incorporate multiple industries, Larch and Wanner (2017) also examine the pledges made by the countries in the Copenhagen Accord. They find that adoption of carbon tariffs by these countries helps lower the leakage rate from 13.4% to 4.1% but also significantly reduce welfare in developing countries. In this paper, I contribute to this literature in three broad ways. First, I employ a trade model with input-output linkages between industries which allows me to account for the indirect effects of carbon pricing created through the use of outputs as inputs in other industries. I also quantify the additional cost of carbon that arises to achieve Canada's commitment under the Paris Agreement and the resulting carbon leakage. Finally, I examine the heterogeneous effects of this policy on output and welfare at the provincial and national levels.

The rest of the paper proceeds as follows. Section 2.2 presents the model. Section 2.3 describes the data and the calibration of the model. Section 2.4 shows the results of the counterfactual scenarios and the last section concludes.

2.2 A Model of Trade and the Environment

Building on the multi-industry trade model with input-output linkages developed by Caliendo and Parro (2015), this section presents a static quantitative model that illustrates the effects of a change in the carbon tax on production, trade patterns and welfare at the provincial level in Canada.

The model describes a world with N regions indexed by i and n, and J industries indexed by j and k. There are $N = 12$ regions, representing the 10 provinces and Yukon, plus a constructed rest of the world (RoW).[2] The model describes the regional production and consumption patterns based on connections between provinces and the rest of the world via bilateral trade flows at the interprovincial and international levels. Every region produces a continuum of varieties in each one of the $J = 22$ industries. Industry-level outputs are then consumed by households and used as inputs in the production of other goods. Production requires two primary factors, labour and fossil fuels, and materials. Burning fossil fuels during production causes CO_2 emissions, the larger the emissions of a producer, the more output it produces. For simplicity, I assume a one-to-one relationship between fossil fuel use and emissions. Benefiting from this correlation between fossil fuel use and emissions, I define CO_2 emissions as an input, omitting fossil fuels in the formulation of production. Even in the absence of a comprehensive carbon tax, existing fossil fuel taxes put an implicit price on emissions, so producers cannot increase output by polluting more for free. This is a fairly standard assumption in the environmental literature (See for example Copeland and Taylor (1994), Fowlie (2009) and Levinson and Taylor (2008)). CO_2 emissions do not exert any negative externalities on consumers or producers. Changes in the cost of CO_2 emissions are exogenously determined.

Each region has a fixed endowment of labour which can move freely between industries

[2] Nunavut and Northwest Territories are excluded from the analysis due to lack of data.

but not across regions. Emissions are supplied elastically in every region at a specific price. Industries are interrelated by input-output linkages. Producers source materials from the lowest cost supplier, whether home or abroad, and trade patterns are determined by productivity differences and trade costs.

2.2.1 Households' Problem

A representative consumer in region n is endowed with L_n units of labour which is mobile across industries but not across regions. Consumers generate income by supplying labour and by receiving transfers. For this analysis, I assume that all carbon tax revenues are recycled back to consumers in the form of lump-sum transfers. Given the level of income, consumers maximize utility by allocating consumption over final goods from all industries. Consumer preferences are then given by

$$U_n = \prod_{j=1}^{J} C_n^{j\,\alpha_n^j} \tag{2.1}$$

where C_n^j is the final good in industry j. Due to Cobb-Douglas preferences across industries, a representative consumer in region n spends α_n^j of its expenditures on industry j goods with $\sum_{j=1}^{J} \alpha_n^j = 1$.

The problem of a consumer in region n is then given by

$$U_n \equiv \max_{\{C_n^j\}_{j=1}^J} \prod_{j=1}^{J} C_n^{j\,\alpha_n^j} \quad \text{subject to} \quad \sum_{j=1}^{J} P_n^j C_n^j = I_n \tag{2.2}$$

2.2.2 Production Technology

Two types of goods are produced in each industry, intermediate goods and final goods which are used as materials in the production of intermediates. Final goods in each industry are produced by perfectly competitive firms as CES aggregates of a continuum of intermediate goods:

$$Q_n^j = \left[\int_0^1 q_n^j(\omega)^{1-1/\sigma^j} d\omega \right]^{\sigma^j/(\sigma^j-1)} \tag{2.3}$$

where σ^j is the elasticity of substitution across intermediate goods and $q_n^j(\omega)$ is the amount demanded of an intermediate good of variety ω from the lowest cost supplier to produce the final good. Intermediate goods can be imported from another region or sourced from domestic producers. Final goods are consumed by households and used by intermediate goods producers as materials. Unlike intermediate goods, final goods are not tradable. The production technology for final goods and the perfectly competitive market structure imply that the unit price of a final good in industry j is given by

$$P_n^j = \left[\int_0^1 p_n^j(\omega)^{1-\sigma^j} d\omega \right]^{1/(1-\sigma^j)} \tag{2.4}$$

where $p_n^j(\omega)$ is the price of an intermediate good of variety ω in industry j. Given Cobb-Douglas preferences, the corresponding consumption price index in region n is $P_n = \prod_{j=1}^J (P_n^j/\alpha_n^j)^{\alpha_n^j}$.

In each industry, a continuum of intermediate goods $\omega \in [0,1]$ is produced using labour, CO_2 emissions and materials. Intermediate goods producers differ in idiosyncratic productivity levels denoted by $z_n^j(\omega)$ and operate in a perfectly competitive environment. The production technology of intermediate good ω is described by

$$q_n^j(\omega) = z_n^j(\omega) \left[e_n^j(\omega)^{\beta_n^j} \; l_n^j(\omega)^{1-\beta_n^j} \right]^{\gamma_n^j} \prod_{k=1}^J m_n^{k,j}(\omega)^{\gamma_n^{k,j}} \tag{2.5}$$

where $e_n^j(\omega)$ and $l_n^j(\omega)$ are the demands for CO_2 emissions and labour, and $m_n^{k,j}(\omega)$ is the demand for final goods from industry k used in the production of intermediate good ω in industry j. The parameter β_n^j is the share of CO_2 emissions in production, $\gamma_n^j \geqslant 0$ is the share of value-added in industry j, and $\gamma_n^{k,j} \geqslant 0$ is the share of final goods from industry k used in the production of intermediate good ω in industry j. Production of intermediate goods are constant returns to scale, so $\sum_{k=1}^{J} \gamma_n^{k,j} + \gamma_n^j = 1$.

The unit cost of intermediate good ω with productivity level $z_n^j(\omega)$ is determined by the following problem

$$
\begin{aligned}
\min_{\{e_n^j(\omega), l_n^j(\omega), m_n^{k,j}\}_{j=1}^{J}} \quad & r_n e_n^j(\omega) + w_n l_n^j(\omega) + \sum_{k=1}^{J} P_n^k m_n^{k,j} \\
\text{subject to} \quad & z_n^j(\omega) \left[e_n^j(\omega)^{\beta_n^j} \; l_n^j(\omega)^{1-\beta_n^j} \right]^{\gamma_n^j} \prod_{k=1}^{J} m_n^{k,j}(\omega)^{\gamma_n^{k,j}} = 1
\end{aligned}
$$

where w_n is the wage rate, r_n is the cost of CO_2 emissions, and P_n^k is the price of final goods from industry k.

Perfect competition and constant returns to scale structure of production technology imply that the minimum cost of an input bundle for producing good ω is given by

$$
c_n^j = \Upsilon_n^j \left(r_n^{\beta_n^j} \; w_n^{1-\beta_n^j} \right)^{\gamma_n^j} \prod_{k=1}^{J} P_n^{k \;\; \gamma_n^{k,j}} \tag{2.6}
$$

where $\Upsilon_n^j = \left(\beta_n^{j \; -\beta_n^j} \; (1-\beta_n^j)^{-(1-\beta_n^j)} \right)^{\gamma_n^j} \; \prod_{k=1}^{J} \gamma_n^{k,j \; -\gamma_n^{k,j}}$.

The market clearing condition for final goods in region n implies that the amount of final goods supplied in industry j is equal to the total demand by the representative consumer and the intermediate goods producers in all industries:

$$
Q_n^j = C_n^j + \sum_{k=1}^{J} \int_0^1 m_n^{j,k}(\omega) \; d\omega \tag{2.7}
$$

2.2.3 Prices and Trade Patterns

Producers of intermediate goods source materials from the lowest cost supplier. Final goods are not tradable but regions trade in the intermediate inputs used in the production of final goods. Trade is costly both within and outside Canada and the trade costs are of the "iceberg" type. Delivering one unit of an intermediate good in industry j from region i to region n requires producing $d^j_{ni} \geqslant 1$ units, there is no trade cost within a region, i.e. $d^j_{nn} = 1$, and triangular inequality holds, $d^j_{nh} d^j_{hi} \geqslant d^j_{ni}$ for all n, i, h. Markets are perfectly competitive and production is constant returns to scale, so suppliers charge prices equal to unit costs. Trade patterns are then determined by technology, factor prices and trade costs.

The producer price of a particular good ω in region i is equal to $c^j_i / z^j_i(\omega)$. Taking trade costs into account, the price paid for a good in region n produced by region i is $p^j_n(\omega) = c^j_i d^j_{ni} / z^j_i(\omega)$. Final goods producers in region n minimize costs and source good ω at the lowest price available. Therefore, the price of an intermediate good ω in industry j and region n is given by

$$p^j_n(\omega) = \min_i \left\{ \frac{c^j_i d^j_{ni}}{z^j_i(\omega)} \right\} \tag{2.8}$$

Firms differ in productivity. Following Eaton and Kortum (2002), the productivity in producing good ω in industry j and region n, $z^j_n(\omega)$, is the realization of a random variable drawn from a Fréchet distribution:

$$F^j_n(z) = e^{-T^j_n z^{-\theta^j}} \tag{2.9}$$

where $T^j_n \geqslant 0$ is an industry and region specific location parameter and θ^j is an industry specific shape parameter. The location parameter determines the level of the distribution and captures the state of technology in industry j, region n. A larger T^j_n makes the average productivity higher. The shape parameter captures the spread of the distribution and a larger θ^j implies the variability in productivity draws are smaller and the draws are closer to the mean. A larger θ^j, which implies a smaller dispersion in productivity levels, generates a smaller price dispersion across goods. I assume that all productivity draws are independent across goods, industries, and regions and that $1 + \theta^j > \sigma^j$ holds. Given the assumptions on the productivity distribution, price of a final good in industry j can be obtained as

$$P_n^j = \eta^j \Big[\sum_{i=1}^{N} T_i^j \ (c_i^j d_{ni}^j)^{-\theta^j} \Big]^{-1/\theta^j} \tag{2.10}$$

where η^j is a constant.[3]

To derive the expression for trade flows, let X_{ni}^j denote the expenditures of region n on industry j goods from region i and X_n^j denote region n's total expenditures (by households and firms) on industry j goods. Then, $\pi_{ni}^j = X_{ni}^j / X_n^j$ is the fraction of region n's expenditures on industry j goods from region i. Using the properties of the productivity distribution, the share of region n's spending on industry j goods from region i is given by[4]

$$\pi_{ni}^j = \frac{T_i^j \left[c_i^j d_{ni}^j \right]^{-\theta^j}}{\sum_{h=1}^{N} T_h^j \left[c_h^j d_{nh}^j \right]^{-\theta^j}} \tag{2.11}$$

Given total expenditures and trade shares, total exports of industry j goods from region n is $\sum_{i \neq n}^{N} \pi_{in}^j X_i^j$ and the amount of domestic sales is $\pi_{nn}^j X_n^j$. Combining total exports and domestic sales yields total revenue in region n from industry j goods:

$$R_n^j = \sum_{i=1}^{N} \pi_{in}^j X_i^j \tag{2.12}$$

Industry revenues may not be equal to expenditures. Industry-level trade deficits are then defined as the difference between imports and exports

$$D_n^j = \sum_{i \neq n}^{N} \pi_{ni}^j X_n^j - \sum_{i \neq n}^{N} \pi_{in}^j X_i^j \tag{2.13}$$

so $D_n^j = X_n^j - R_n^j$.

[3] $\eta^j = \Gamma(1 + (1 - \sigma^j)/\theta^j)^{1/(1-\sigma^j)}$ and $\Gamma(.)$ is the Gamma function.

[4] See B.1 for the derivation of price indices and bilateral trade shares.

The production technologies imply that in each industry, a fraction γ_n^j of firm revenues go to factors. And total income in region n is the sum of labour income, revenue from the payments to CO_2 emissions and the trade deficit:

$$I_n = \sum_{j=1}^{J} \gamma_n^j R_n^j + D_n \tag{2.14}$$

Finally, total expenditure on industry j goods is the sum of expenditures on final goods by firms and consumers and is given by

$$X_n^j = \sum_{k=1}^{J} \gamma_n^{j,k} \sum_{i=1}^{N} \pi_{in}^k X_i^k + \alpha_n^j I_n \tag{2.15}$$

2.2.4 Factor Markets

Labour demand in the production of good ω in industry j is $l_n^j(\omega)$. Total labour demand in industry j is then equal to $L_n^j = \int_0^1 l_n^j(\omega)\, d\omega$. In region n, total labour supply is fixed and equal to L_n, therefore the labour market clearing condition requires that labour supply equals total labour demand, $L_n = \sum_{j=1}^{J} L_n^j$. Labour's share in the production of industry j goods is given by $1 - \beta_n^j$. Then, the labour earnings in industry j are equal to

$$w_n L_n^j = (1 - \beta_n^j)\gamma_n^j \sum_{i=1}^{N} \pi_{in}^j X_i^j \tag{2.16}$$

In every region, CO_2 emissions are elastically supplied at an implicit price r_n. At r_n, the demand for CO_2 emissions by a firm producing good ω is $e_n^j(\omega)$ and total demand in industry j is $E_n^j = \int_0^1 e_n^j(\omega)\, d\omega$. Then in region n, $E_n = \sum_{j=1}^{J} E_n^j$ units of CO_2 emissions are used in the production of intermediate goods. Total revenue generated in industry j from the taxation of CO_2 emissions is a fraction β_n^j of the value-added:

$$r_n E_n^j = \beta_n^j \gamma_n^j \sum_{i=1}^{N} \pi_{in}^j X_i^j \tag{2.17}$$

Then, from equations (2.16) and (2.17), demand for CO_2 emissions in industry j is

$$E_n^j = \frac{w_n}{r_n} \frac{\beta_n^j}{1 - \beta_n^j} L_n^j \tag{2.18}$$

And, the total use of CO_2 emissions in region n is therefore given by

$$E_n = \frac{w_n}{r_n} \sum_{j=1}^{J} \frac{\beta_n^j}{1 - \beta_n^j} L_n^j \tag{2.19}$$

2.2.5 General Equilibrium

In every region, consumers maximize utility, firms maximize profits and all markets clear. Trade may not be balanced at the regional or industry level. In region n, market clearing implies that total revenues from intermediate goods exported are equal to n's total imports minus the aggregate trade deficit:

$$\sum_{j=1}^{J} \sum_{i=1}^{N} \pi_{in}^j X_i^j = \sum_{j=1}^{J} \sum_{i=1}^{N} \pi_{ni}^j X_n^j - D_n \tag{2.20}$$

Definition 2.1. A general equilibrium in this economy is a set of wages $\{w_n\}_{n=1}^N$, labour allocations, CO_2 emissions $\{E_n\}_{n=1}^N$, and prices $\{P_n^j\}_{n,j=1}^{N,J}$ such that given aggregate labour supplies $\{L_n\}_{n=1}^N$, trade costs $\{d_{ni}^j\}_{n,i,j=1}^{N,I,J}$, aggregate trade imbalances $\{D_n\}_{n=1}^N$, parameters of the productivity distribution $\{T_n^j\}_{n,j=1}^{N,J}$, $\{\theta^j\}_{j=1}^J$, and the cost of CO_2 emissions $\{r_n\}_{n=1}^N$, equations (2.6), (2.10), (2.11), (2.15), and (2.20) hold for all j, n.

2.2.6 Equilibrium in Relative Changes

The model can be solved for changes in equilibrium outcomes in response to a change in environmental policy. As suggested by Dekle et al. (2008), I reformulate the model and express the equilibrium in relative changes instead of solving for the complete model. Using this approach significantly reduces the number of variables necessary to do a counterfactual analysis. Denote the ratio of counterfactual to initial values as $\hat{x} = \frac{x'}{x}$ where $\hat{x}$ represents a relative change in a variable x. The equilibrium conditions in relative changes in response to a change in environmental policy represented by $\hat{r}_n$ satisfy the following equations.

From equation (2.6), the changes in input costs are

$$\hat{c}_n^j = \hat{r}_n^{\;\beta_n^j \gamma_n^j} \; \hat{w}_n^{\;(1-\beta_n^j)\gamma_n^j} \prod_{k=1}^{J} \hat{P}_n^{k \;\; \gamma_n^{k,j}} \tag{2.21}$$

and the changes in industry prices are

$$\hat{P}_n^j = \left[\sum_{i=1}^{N} \pi_{ni}^j [\hat{c}_i^j]^{-\theta^j} \right]^{-1/\theta^j} \tag{2.22}$$

The bilateral trade shares change according to

$$\hat{\pi}_{ni}^j = \left[\frac{\hat{c}_i^j}{\hat{P}_n^j} \right]^{-\theta^j} \tag{2.23}$$

where the new set of bilateral trade shares is given by:

$$\pi_{ni}^{j\;\prime} = \frac{\pi_{ni}^j [\hat{c}_i^j]^{-\theta^j}}{\sum_{h=1}^{N} \pi_{nh}^j [\hat{c}_h^j]^{-\theta^j}} \tag{2.24}$$

The counterfactual total expenditure in each region n and industry j is

$$X_n^{j\prime} = \sum_{k=1}^{J} \gamma_n^{j,k} \sum_{i=1}^{N} \pi_{in}^{k\;\prime} X_i^{k\prime} + \alpha_n^j I_n' \tag{2.25}$$

where the counterfactual level of income is given by

$$I_n' = \hat{w}_n w_n \sum_{j=1}^{J} \frac{1}{1-\beta_n^j} L_n^{j\;\prime} + D_n \tag{2.26}$$

and the counterfactual labour allocations are given by

$$L_n^{j\,\prime} = \frac{1}{\hat{w}_n w_n}(1-\beta_n^j)\gamma_n^j \sum_{i=1}^{N} \pi_{in}^{j\,\prime} X_i^{j\prime} \tag{2.27}$$

Finally, the counterfactual trade balance is

$$\sum_{j=1}^{J}\sum_{i=1}^{N} \pi_{in}^{j\,\prime} X_i^{j\prime} = \sum_{j=1}^{J}\sum_{i=1}^{N} \pi_{ni}^{j\,\prime} X_n^{j\prime} - D_n \tag{2.28}$$

Using the searching algorithm proposed by Caliendo and Parro (2015), this system of equations of equilibrium changes can be solved to evaluate the counterfactuals. The algorithm assumes an initial vector of wages, computes prices, trade shares, and the new levels of expenditures based on this vector and the exogenously imposed change in implicit cost of carbon, and then evaluates the trade balance condition to adjusts the wage changes until the equilibrium is found. Then, I study the effects of stricter carbon policies on three main outcomes, welfare, carbon emissions and trade flows.

Counterfactual Welfare

The relative change in welfare from the benchmark equilibrium is determined by the relative change in real income

$$\hat{W}_n = \frac{\hat{I}_n}{\hat{P}_n} \tag{2.29}$$

where the change in income is derived from equation (2.14) and change in the consumer price index is calculated from the change in industry prices given by equation (2.22).[5] The determinants of the welfare change are changes in wages and carbon tax. Counterfactual wages are solved at the general equilibrium and counterfactual carbon tax is exogenously given. There can be significant changes in welfare of regions with no change in the cost of carbon because changes in other regions propagate through the economy via the effect of

[5]Under this notation, $\hat{W}_n$ represents the relative change in welfare under $r_n{}'$ relative to r_n, namely $\hat{W}_n = \frac{W_n{}'}{W_n}$.

trade and input-output linkages on wages.

Counterfactual Emissions and Carbon Leakage

From equation (2.18), the counterfactual level of CO_2 emissions in response to a change in environmental policy is

$$E_n^{j\prime} = \frac{\hat{w}_n w_n}{r_n{}'} \frac{\beta_n^j}{1-\beta_n^j} L_n^{j\prime} \tag{2.30}$$

Summing over all j, the counterfactual set of aggregate CO_2 emissions in region n is given by

$$E_n{}' = \sum_{j=1}^{J} E_n^{j\prime} = \frac{\hat{w}_n w_n}{r_n{}'} \sum_{j=1}^{J} \frac{\beta_n^j}{1-\beta_n^j} L_n^{j\prime} \tag{2.31}$$

In the literature, the aggregate impact on industrial emissions is often broken into three separate effects (See for example Grossman and Krueger (1991) and Copeland and Taylor (1994)). I use this decomposition to examine how provincial industrial emission levels are affected by exogenous changes in carbon policy. Holding everything else constant, the scale effect measures the change in the level of emissions created by a change in the level of economic activity following a policy change. Following the introduction of a carbon tax, producers adjust by substituting between dirty and clean actors of production. The technique effect refers to these changes in inputs and intermediate goods used in production. Finally, the composition effect refers to the effect of a change in the mix of goods produced in an economy on total emissions. In section 2.4, I report the shares of these three effects in the overall changes in emissions.

From equation (2.17) and the definition of total industry revenues given in equation (2.12), the total industry emissions in region n can be written as

$$E_n = \frac{1}{r_n} \sum_{j=1}^{J} \beta_n^j \gamma_n^j R_n^j \tag{2.32}$$

Defining total revenues in region n as $\tilde{R}_n = \sum_{j=1}^{J} R_n^j$, industry shares of value-added in total regional revenues as $s_n^j = \gamma_n^j R_n^j / \tilde{R}_n$, and region n's weighted average emissions cost share as $\tilde{\beta}_n = \sum_{j=1}^{J} \beta_n^j s_n^j$, I rewrite total emissions in region n in terms of average cost share of emissions in total production, real cost of emissions and real income:

$$E_n = \tilde{\beta}_n \frac{P_n}{r_n} \frac{\tilde{R}_n}{P_n} \tag{2.33}$$

Taking the total differential of equation (2.33) decomposes the change in total emissions in region n into scale, technique and composition effects:

$$\mathrm{d}E_n = \underbrace{\frac{\partial E_n}{\partial(\tilde{R}_n/P_n)} \mathrm{d}(\tilde{R}_n/P_n)}_{\text{scale effect}} + \underbrace{\frac{\partial E_n}{\partial(r_n/P_n)} \mathrm{d}(r_n/P_n)}_{\text{technique effect}} + \underbrace{\frac{\partial E_n}{\partial \tilde{\beta}_n} \mathrm{d}\tilde{\beta}_n}_{\text{composition effect}} \tag{2.34}$$

Assuming that the composition and technology of production remains unchanged, the scale effect captures the impact of a change in economic activity on emissions. For example, an economic contraction following the introduction of carbon tax reduces total emissions. Therefore, the scale effect is positive and proportional to real revenues:

$$\frac{\partial E_n}{\partial(\tilde{R}_n/P_n)} = \frac{\tilde{\beta}_n}{r_n/P_n} > 0 \quad \text{and} \quad \frac{\partial E_n}{\partial(\tilde{R}_n/P_n)} \frac{\tilde{R}_n/P_n}{E_n} = 1 \tag{2.35}$$

The input-output linkages have an impact on the scale effect. Assume that the average value-added share of production is relatively small in region n and intermediate inputs from other industries are heavily used (meaning a small γ_n^j for all j), this means a relatively small average emission intensity in region n ($\tilde{\beta}_n$). Then, an economic expansion will have a relatively small impact on total emissions in region n, hence the scale effect will be small.

Holding the level of economic activity and the composition of production constant, stricter carbon policy encourages firms to shift towards cleaner production processes and reduce total emissions. This impact of carbon taxes is captured by the technique effect:

$$\frac{\partial E_n}{\partial(r_n/P_n)} = -\frac{\tilde{\beta}_n \tilde{R}_n/P_n}{(r_n/P_n)^2} < 0 \quad \text{and} \quad \frac{\partial E_n}{\partial(r_n/P_n)} \frac{r_n/P_n}{E_n} = -1 \tag{2.36}$$

Again notice the role of intermediate inputs in determining the power of the technique effect. A large share of intermediate inputs in production (resulting in a small average emission intensity of production $\tilde{\beta}_n$) means that a stricter carbon policy will have a relatively small impact on reducing emissions.

Finally, the composition effect measures the change in emissions in a region due to a change in the composition of goods produced as different regions specialize in certain industries in which they have a comparative advantage:[6]

$$\frac{\partial E_n}{\partial \tilde{\beta}_n} = \frac{\tilde{R}_n}{r_n} > 0 \quad \text{and} \quad \frac{\partial E_n}{\partial \tilde{\beta}_n} \frac{\tilde{\beta}_n}{E_n} = 1 \tag{2.37}$$

The increase in emissions due to the composition effect is proportional to the increase in the average emissions cost share, $\tilde{\beta}_n$. If in region n, the production shifts towards relatively more pollution intensive goods (with higher β_n^j), holding total revenues and carbon tax constant, share of revenue generated from these goods increases and emissions increase.

Unilateral changes in carbon policy may shift emissions between regions. To calculate the extent of carbon leakage in the counterfactual scenarios, a common measure employed in the literature is the amount of emissions increase in regions with no carbon price shock divided by the amount of emissions savings in all regions as a result of a change in the price of carbon. In all regions $n \notin N^L$ there is no change in the price of carbon, then the emission increase in these regions induced by the stricter carbon regulations in regions $n \in N^L$ is given by $\sum_{n \notin N^L}({E_n}' - E_n)$. In all regions with a change in the price of carbon, total decrease in emissions is given by $\sum_{n \in N^L}({E_n}' - E_n)$. Therefore, the aggregate emission relocation in

[6]Notice that composition effect is present only in a multi-industry environment.

percentages is

$$E^L = \frac{\sum_{n \notin N^L} ({E_n}' - E_n)}{-\sum_{n \in N^L} ({E_n}' - E_n)} 100 \tag{2.38}$$

Counterfactual Trade Flows

From the definition of bilateral trade shares, trade flows between region n and i in industry j goods are defined as

$$X^j_{ni} = \pi^j_{ni} X^j_n \tag{2.39}$$

Then, using equation (2.23), the change in trade flows can be written as

$$\hat{X}^j_{ni} = \hat{X}^j_n \left[\frac{\hat{c}^j_i}{\hat{P}^j_n} \right]^{-\theta^j} \tag{2.40}$$

The reaction of trade flows to carbon policy shocks is then determined by the changes in the market size, the cost of goods in the exporting region and the prices in the importing region.

It is also informative to evaluate the changes in the emissions content of trade flows. Emissions embodied in the imports of region n from region i in industry j can be obtained from equation (2.17) as

$$e^j_{ni} = \frac{\beta^j_i \gamma^j_i}{r_i} X^j_{ni} \tag{2.41}$$

Then, in response to a change in carbon prices in all regions, emissions embodied in trade flows change accordingly:

$$\hat{e}^j_{ni} = \frac{\hat{X}^j_{ni}}{\hat{r}_i} \tag{2.42}$$

In section 2.4, for every policy experiment, I also report the changes in emission content of trade. Simply summing equation (2.41) over all j and dividing by the importer's total emissions, I obtain the emission imports from region i as a share of total domestic emissions, $\frac{\sum_{j=1}^{J} \beta_i^j \gamma_i^j X_{ni}^j}{E_n r_i}$. The change in the extent of this measure of emission imports depends on direct ($\hat{r}_i$) and general equilibrium ($\hat{E}_n$, $\hat{X}_{ni}^j$) effects and may rise or fall in the counterfactual.

2.3 Calibration and Data

Before quantifying the relative effects of a change in carbon taxes on provincial outcomes, I first need to calibrate the model parameters (β_n^j, γ_n^j, $\gamma_n^{k,j}$, α_n^j) and obtain necessary variables (π_{ni}^j, D_n, E_n^j) using available data. The regional data needed to perform the quantitative analysis are the gross output, gross value added, total employment, bilateral trade flows, and the input-output (IO) tables. I use data from various sources to calibrate the model to the base year, 2011. The choice of the base year is driven by the need to construct the largest data set possible on bilateral trade and CO_2 emissions. In this section I briefly describe the underlying data sources and present the calibration strategy.

The main data source used to calibrate the model is the provincial and territorial supply and use tables (SUT) from Statistics Canada's CANSIM database. The Canadian SUTs break down the economy into 236 industries and 496 product groups. To calculate the production technology parameters (γ_n^j, $\gamma_n^{k,j}$) and the final demand shares (α_n^j), I first construct provincial symmetric input-output tables from the SUTs. SUTs are available at both purchaser and basic prices. For input-output purposes, I employ the use tables valued at basic prices. I do not use Statistics Canada's provincial IO tables since the level of aggregation in these tables for the manufacturing industry does not match the required level of detail in this analysis. Manufacturing industries in different regions differ a lot in terms of emissions intensity and trade exposure but the manufacturing industries in the SUTs are aggregated into a single industry in the provincial IO tables of Statistics Canada. Since analysing the effect of carbon tax on industries with different emissions and trade intensities is the main focus of this paper, I construct provincial IO tables with 22 industries seven of which are manufacturing industries. To calculate the same parameters for the rest of the world, I use the world IO tables and the exchange rates from the World Input-Output Database (WIOD). The list of industries is reported in Table 2.1.

Table 2.1: The List of Industries

Number	Industry	ISIC Rev. 3
1	Agriculture and Forestry	01-05
2	Mining	10-14
3	Food and Textiles	15-19
4	Wood	20
5	Paper	21-22
6	Chemicals	23-26
7	Metals	27-28
8	Machinery and Equipment	29-35
9	Manufacturing, n.e.c.	36-37
10	Utilities	40-41
11	Construction	45
12	Wholesale and Retail	50-52
13	Hotels and Restaurants	55
14	Transportation	60-63
15	Communication	64
16	Finance	65-71
17	Computer and Related Activities	72-73
18	Other Business Activities	74
19	Public Administration	75
20	Education	80
21	Health and Social	85
22	Other Services	90-93

To obtain the industry shares of CO_2 emissions in production (β_n^j), I must first obtain the industrial emissions in each region (E_n^j). SUTs provide the value of various energy sources used by each industry in Canadian dollars. The fossil fuel products available in the SUTs are gasoline, diesel, light fuel oils, natural gas, jet fuel, heavy fuel oil, propane and coal. Using the provincial and federal price data for each of these fossil fuels compiled from various sources and the emission factors from the National Inventory Report (NIR) for the year 2011, I calculate industry-level CO_2 emissions from energy use in each region. The reason why I calculate the embodied emissions myself is the different industry aggregation used by the NIR. The NIR provides detailed provincial and territorial emissions data based on the United Nations Framework Convention on Climate Change (UNFCCC) classification of industries and for this reason, the industry classification used in the SUTs of Statistics Canada cannot be directly mapped to the industry-level emissions in the NIR. To calculate the emissions in the constructed rest of the world, I use the WIOD Environmental Accounts.

Table 2.2 displays my calculations of the sources of industrial CO_2 emissions in every province by fuel type. Natural gas is a common source of energy in most provinces, mainly in power generation. Coal is another common source of industrial emissions. Newfoundland, Yukon and Prince Edward Island are exceptions with no industrial natural gas or coal use. These three regions generate most of their electricity from hydro sources. In 2016, hydroelectricity accounted for 95% of Newfoundland's total power supply, 2% was from petroleum, 2% was from natural gas, and 1% was from wind, but the SUTs show no industrial use of natural gas in Newfoundland for 2011. Heavy fuel oil accounts for 71% of Newfoundland's industrial emissions. The main users of this very emission intensive fuel in Newfoundland are the petroleum refineries and the oil and gas extraction industry. Yukon generates 95% of its electricity from hydro sources and 5% from petroleum. About 98% of electricity generation in Prince Edward Island is from wind farms, 1% is from petroleum and the rest is from biomass and geothermal. In Nova Scotia, the primary source of electricity generation is coal and the CO_2 emissions from coal make up 65% of the province's total emissions. The high share of coal emissions in Saskatchewan is also due to the structure of power generation in the province. Roughly 98% of the total industrial coal demand in Saskatchewan is from the electricity generation. The same is true for Alberta where about

46% of the electricity is generated from coal.[7] Even if only 6% of the total Canadian industrial coal demand is in British Columbia, because coal is a very emission intensive energy source, it makes 35% of the province's industrial emissions. The industrial fossil fuel use is also relatively low in New Brunswick, and the coal used in power generation makes half of the province's total emissions. In 2003, Ontario committed to phasing out all coal consumption by the end of 2014 and the use of coal in electricity generation was already in decline in 2011. The main user of coal in Ontario is the steel industry. Quebec does not use coal-fired power generation but coal is used in chemicals and steel production which makes 40% of the province's emissions.

Table 2.2: Sources of Industrial CO_2 Emissions, by Province

	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK	YT
Gasoline	4%	8%	10%	5%	6%	4%	7%	17%	9%	4%	20%
Diesel	8%	18%	26%	9%	11%	5%	11%	29%	18%	8%	33%
Light Fuel Oils	1%	2%	3%	3%	5%	4%	2%	35%	4%	1%	15%
Natural Gas	37%	18%	46%	16%	0%	11%	18%	0%	16%	40%	0%
Jet Fuel	2%	10%	7%	1%	3%	3%	4%	2%	5%	1%	24%
Heavy Fuel Oil	2%	6%	2%	11%	71%	7%	1%	13%	4%	1%	6%
Propane	6%	2%	3%	6%	4%	2%	4%	5%	3%	1%	2%
Coal	41%	35%	3%	50%	0%	65%	53%	0%	40%	45%	0%

Note: The table shows the share (in %) of each fuel source in industrial emissions by province. Each column sums up to 100%.

It is important to note that not all fossil fuels in the SUTs are direct emissions sources, there are non-energy uses of fossil fuels, mostly in the chemicals industry. One example of this is the natural gas used as feedstock during ammonia production in the fertilizer industry. The NIR classifies the emissions from feed-fuels as non-combustion industrial process emissions and for each process there is a unique equation to calculate emissions which is based on

[7]For provincial electricity generation by fuel type see the National Energy Board, Provincial and Territorial Energy Profiles.

the corresponding chemical reaction.[8] Currently there is no consensus among provincial and territorial governments on whether or not to cover industrial process emissions in the carbon pricing schemes. The carbon tax in British Columbia does not apply on industrial process emissions.[9] In Alberta, the 2016-2019 Fiscal Plan states that there are industrial exemptions from the carbon levy for non-combustion emissions[10] but the industrial process emissions of the facilities that opt in to the recently announced Carbon Competitiveness Incentives Regulation (CCIR)[11] will be included in the carbon pricing system. The Technical Paper on the Federal Carbon Pricing Backstop released in 2017 by the Environment and Climate Change Canada proposes relief from the carbon levy for feed-fuels used as a raw material in industrial processes.[12] The SUTs do not distinguish between feed-fuels and combustion fuels as inputs. Therefore, I scale down industry-level fuel demand in my calculations to match the NIR data or the provincial inventory reports where examples of these occur and do not include industrial process emissions in the counterfactual exercises.

As mentioned in section 2.2, I assume a linear relationship between fossil fuel use and CO_2 emissions. This allows me to construct a region's implicit cost of CO_2 emissions as $r_n = EC_n/E_n$ where EC_n is the sum of fossil fuel expenses and E_n is the total emissions in region n. The total cost of fossil fuel use is readily available from the provincial SUTs and for the total regional emissions I simply aggregate the industry emissions I calculated previously. After calculating the industry-level cost of emissions for every region, I gather data on gross value added from the IO tables and measure the emissions intensity parameters (β_n^j).

[8]Environment Canada's methodologies for calculating emissions from relevant industrial processes are explained in detail in the Annex 3.2 of National Inventory Reports under Methodology for Industrial Processes.

[9]For carbon tax exemptions in British Columbia, see https://www2.gov.bc.ca/gov/content/taxes/sales-taxes/motor-fuel-carbon-tax/business/exemptions.

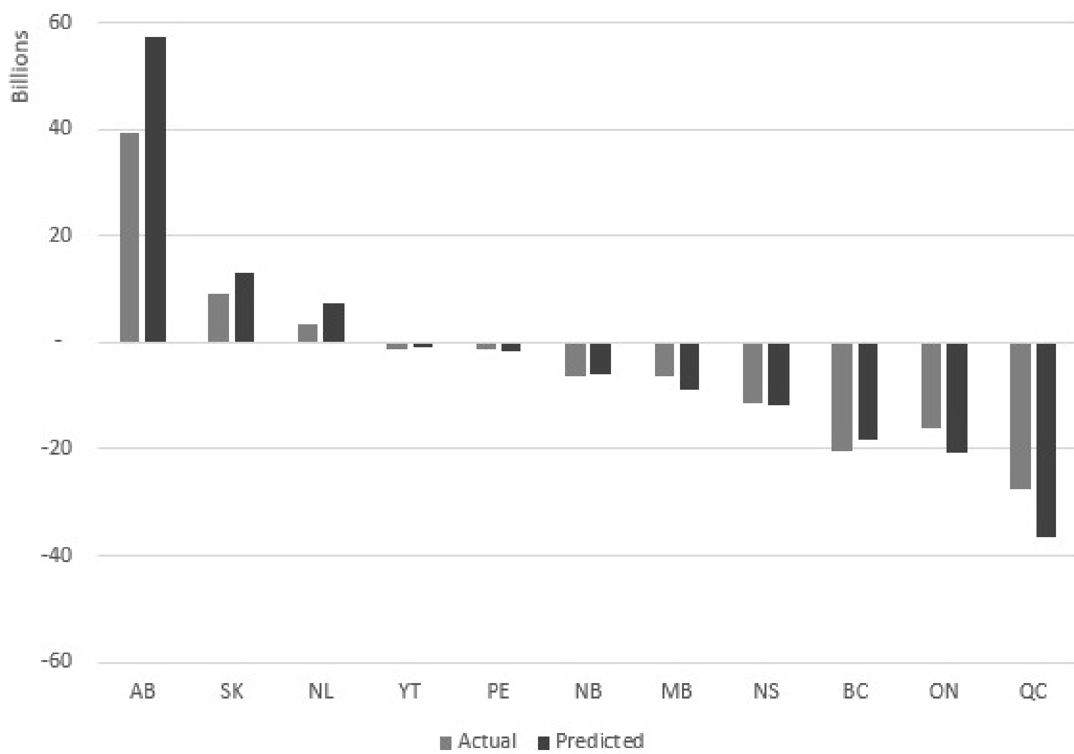
[10]For a list of carbon levy exemptions in the 2016-2019 Fiscal Plan see http://finance.alberta.ca/publications/budget/budget2016/fiscal-plan-complete.pdf

[11]The Carbon Competitiveness Incentives Regulation (CCIR) comes into effect on January 1, 2018 and replaces the current Specified Gas Emitters Regulation (SGER) for industrial facilities that emit over 100,000 tonnes or more of carbon dioxide or equivalent regulated greenhouse gases per year.

[12]For the technical paper, see https://www.canada.ca/en/services/environment/weather/climatechange/technical-paper-federal-carbon-pricing-backstop.html

Statistics Canada's SUTs include estimates of interprovincial and international trade. I aggregate this data into the same industry classification I used for the IO tables. Then, I calculate the bilateral trade shares (π^j_{ni}) for each pair of regions in every industry using this trade data. Trade deficits in each industry j and region n (D^j_n) are also calibrated to match the same bilateral trade data as the difference between bilateral imports and exports in each industry and aggregated to reach regional deficits. The actual and predicted trade imbalances are presented on Figure 2.1. I calculate the counterfactuals holding the aggregate trade deficits constant.

Figure 2.1: Trade Imbalances (CAD, billions)



Estimating industry-specific trade elasticity parameters (θ^j) require data on tariffs or detailed product prices which I do not have at the within-country level. Therefore, I adopt the estimates from Caliendo and Parro (2015). For details on these estimates see Table B.1.

Finally, I obtain the data on total employment for every region (L_n) from Statistics Canada. Global employment data for the constructed rest of the world comes from the annual report of the International Labour Organization (ILO), Global Employment Trends.

Table 2.3: Summary Statistics

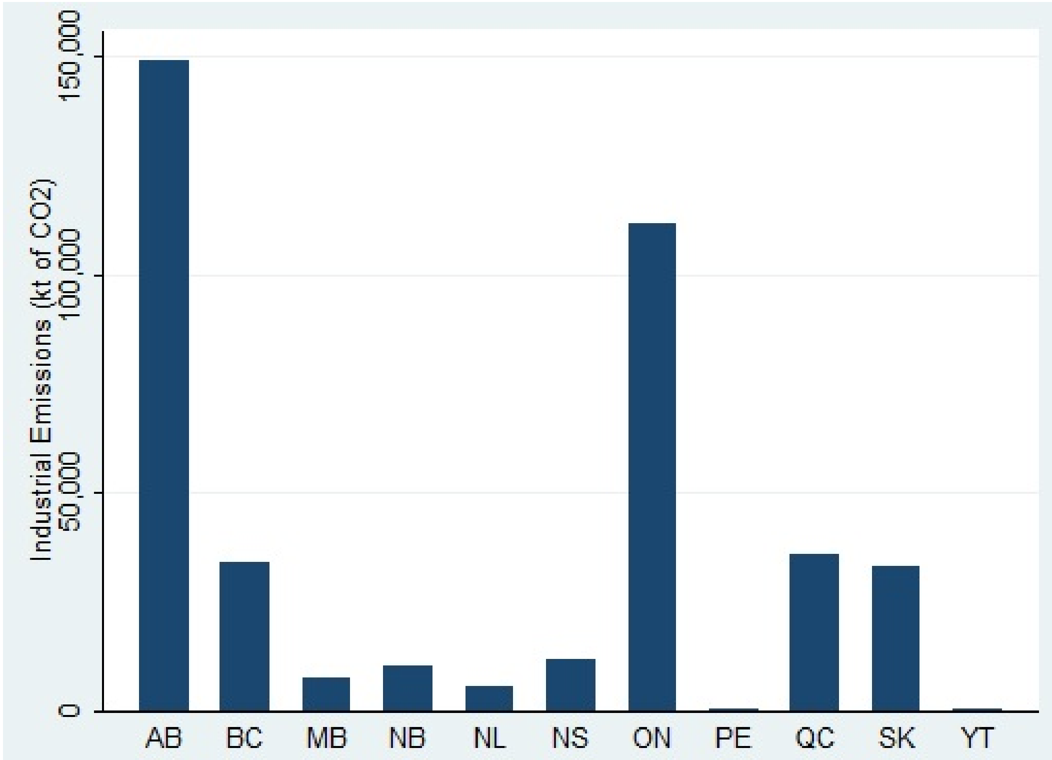
Variable	Obs.	Mean	Std. Dev.	Min	Max
GDP (million $)	11	106,240	121,684	2,494	344,734
Imports-intranational (million $)	2,662	132	482	0	6,702
Imports-international (million $)	3,168	450	2,973	0	87,400
Labour Force (thousands)	11	1,359	1,792	19	5,720
Emissions (kt of CO_2)	11	36,363	49,082	186	149,123
Implicit CO_2 Price ($ per t CO_2)	11	213.02	119.73	92.48	474.73
β_n^j	242	0.046	0.071	0.0004	0.6181

Note: Displays some summary statistics of bilateral and regional variables in 2011. The cost share of emissions (β_n^j) is region-industry specific. RoW is included only in international imports. Monetary variables are in current CAD. See text for details.

Table 2.3 provides summary statistics for the 11 regions of Canada in the dataset and the RoW is excluded from the summary statistics except for bilateral trade. On average, industrial emissions in Canada amount to 36 mega tonnes of CO_2 in 2011. Alberta has the highest industrial emissions with 149 mega tonnes of CO_2 and Yukon has the lowest industrial emissions with 186 kilo tonnes of CO_2. Figure 2.2 displays total industrial emissions in 2011 by province and territory.

The average implicit cost of a tonne of CO_2 in Canada is $213 but there is variation across regions. With below $100, Saskatchewan and Alberta have the lowest implicit CO_2 costs and with above $200 Yukon, Prince Edward Island, Manitoba and Quebec have the highest CO_2 costs. As mentioned earlier, fossil fuel use and emissions are assumed to have a linear relationship. Therefore, the discrepancy across regions in emissions costs are due to

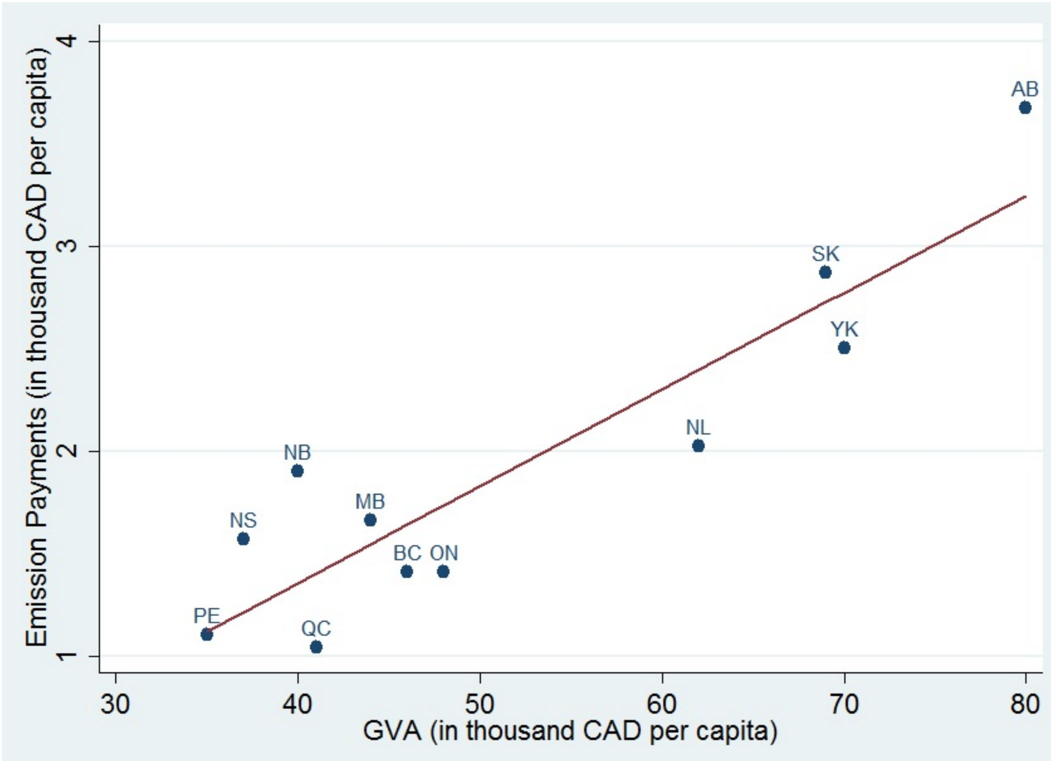
Figure 2.2: Industrial Emissions, by Province and Territory



differences in the prices of fossil fuels at the provincial level. The average cost share of CO_2 emissions is 0.046 with a standard deviation of 0.07. There is variation across industries and provinces in terms of β but in general, chemicals production and utilities have the highest, and services like education and communication have the lowest emission cost shares for most provinces. To see how provinces compare in terms of emissions use, see Figure 2.3 which plots provinces' implicit emission payments against their gross value added. The line on the figure represents a simple OLS regression of emission payments on gross value added. The estimated average emission cost share is 0.047 with a standard error of 0.007. Alberta, New Brunswick, Nova Scotia, Saskatchewan and Manitoba have higher than average and provinces below the line have smaller than average emissions cost shares.

There are 2662 interprovincial trade flows in the data and the average bilateral import between provinces amounts to 132 million \$. Cost of imports from the RoW displays a larger

Figure 2.3: Emissions Payments and GVA, by Province and Territory



variation and the average import from the RoW is 450 million \$. Table 2.4 provides more information on interprovincial and international trade. Overall, 26% of output in Canada is exported. Provinces export 10.6% of their output to other provinces and 15.5% abroad. International trade amounts to about a third of the economy and it is larger than the trade between provinces.

Table 2.4: Trade as a Share of Output

	Interprovincial	International
Exports	10.6%	15.5%
Imports	10.6%	17.1%
Total	21.2%	32.6%

However, the relative weight of international trade differs across provinces. Table 2.5 presents shares of output exported abroad and within Canada at the provincial level. Overall, international trade is more important than interprovincial trade, for example Ontario exports 16% of its output abroad while 9% of its output is traded within Canada. But the opposite is true for Manitoba, Nova Scotia, Prince Edward Island and Yukon. A quarter of Saskatchewan and Newfoundland's output is exported abroad compared to 6% of Yukon's and 10% of Nova Scotia's. There is variation across provinces also in terms of the total shares of output exported. Newfoundland is at the high end of the distribution with 41% compared to Yukon with 16% and British Columbia with 22%.

Table 2.5: Shares of Output Exported

Province	Total Exports	Interprovincial Exports	International Exports
AB	28%	11%	17%
BC	22%	10%	12%
MB	29%	16%	13%
NB	34%	16%	18%
NL	41%	16%	25%
NS	22%	12%	10%
ON	26%	10%	16%
PE	26%	15%	11%
QC	23%	10%	13%
SK	38%	13%	25%
YT	16%	9%	6%

Note: The sums may not add up due to rounding.

The shares of output exported should also be compared at the industry level. Table 3.1 displays this information. Hypothetically, if the cost of CO_2 emissions were equal across Canada, among industries with equal emissions intensities, the ones with the largest international export shares would be more vulnerable to a unilateral change in domestic carbon tax compared to the ones traded mostly within Canada. The data shows that the most heavily exported industries, both internationally and interprovincially, are the manufacturing industries. Overall, mining and the manufacturing industries like metals, wood, chemicals and food and textiles are among the most exported industries. International exports are important mostly for manufacturing industries as well. Metals, machinery and

Table 2.6: Shares of Output Exported, by Industry

Industry	Total Exports	Interprovincial Exports	International Exports
Agriculture and Forestry	40%	14%	27%
Mining	68%	18%	50%
Food and Textiles	57%	34%	23%
Wood	54%	21%	33%
Paper	49%	14%	35%
Chemicals	54%	21%	33%
Metals	67%	15%	52%
Machinery and Equipment	53%	10%	44%
Manufacturing, n.e.c.	69%	23%	46%
Utilities	7%	3%	4%
Construction	1%	1%	0%
Wholesale and Retail	23%	13%	10%
Hotels and Restaurants	25%	13%	12%
Transportation	37%	19%	17%
Communication	18%	13%	4%
Finance	10%	8%	2%
Computer and related activities	51%	24%	26%
Other Business Activities	20%	12%	8%
Public Administration	0%	0%	0%
Education	3%	1%	2%
Health and Social	1%	1%	0%
Other Services	14%	9%	5%

Note: The sums may not add up due to rounding.

equipment, paper are exported more heavily compared to others. More than half of the output in metals production and half of mining output is exported abroad. A similar characteristic can also be seen in the interprovincial trade. A third of the output from food and textiles is traded interprovincially. As one would expect, services are among the least exported and their trade happens mainly inside Canada.

Input-output linkages across industries propagate and may amplify the effects of changes in carbon taxes. Using the provincial IO tables, I construct a similar IO table for Canada. Table 2.7 shows the input-output shares from this aggregate IO table. These shares are the intensities of input-use of each industry from every other industry. The table shows, for each column, the share of inputs that comes from each row. Production mainly depends on inputs from the same industry but strong interdependencies are visible, one example is between the emissions-intensive mining industry and the chemicals and metals production. There are also less emissions intensive industries on the basis of their direct emissions which supply considerable shares of their inputs from emissions intensive industries. For example, chemicals and metals provide one third of the inputs of the construction industry. The theoretical model allows me to observe how the impact of changes in carbon tax spread through the economy via these interdependencies between industries.

2.4 Quantifying the Trade and Welfare Effects of Climate Policy Scenarios

After calibrating the model against available data, I now turn to examining the effects of emission reduction targets. In this section, I conduct policy experiments to evaluate the effects from exogenous changes in carbon pricing in Canada. The model is simulated using bilateral trade in 22 industries for 10 provinces, Yukon and a constructed RoW in 2011. The choice of year is driven by the need to construct the largest data set from the available data.

I start with a policy experiment to show the effects of Canada's commitment in the Paris Climate Agreement to reduce its emissions by 30% below 2005 levels. Then, I develop another counterfactual climate policy scenario to show the role of output based allocations (OBAs) in reducing carbon leakage from Canada's NDC.

Table 2.7: Input-Output Shares in Canada (2011)

	01-05	10-14	15-19	20	21-22	23-26	27-28	29-35	36-37	40-41	45	50-52	55	60-63	64	65-71	72-73	74	75	80	85	90-93
01-05	**0.32**	0.00	0.37	0.39	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01
10-14	0.02	**0.24**	0.01	0.01	0.01	0.48	0.27	0.00	0.27	0.21	0.10	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.02	0.01	0.01
15-19	0.11	0.00	**0.25**	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.35	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.05
20	0.00	0.00	0.00	**0.18**	0.07	0.00	0.00	0.01	0.01	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21-22	0.00	0.00	0.03	0.00	**0.27**	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.02	0.00	0.06	0.01	0.13
23-26	0.17	0.09	0.04	0.06	0.10	**0.29**	0.06	0.10	0.08	0.07	0.16	0.04	0.01	0.16	0.03	0.01	0.00	0.03	0.08	0.04	0.08	0.07
27-28	0.01	0.05	0.01	0.01	0.01	0.01	**0.45**	0.13	0.21	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
29-35	0.09	0.12	0.02	0.06	0.06	0.02	0.04	**0.47**	0.03	0.05	0.11	0.03	0.05	0.09	0.20	0.05	0.10	0.07	0.03	0.07	0.10	0.14
36-37	0.00	0.00	0.01	0.02	0.02	0.01	0.01	0.01	**0.13**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.08	0.01
40-41	0.02	0.03	0.02	0.03	0.07	0.02	0.03	0.01	0.01	**0.03**	0.00	0.02	0.02	0.01	0.01	0.02	0.00	0.00	0.02	0.05	0.04	0.02
45	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.16	**0.00**	0.01	0.02	0.03	0.00	0.10	0.01	0.01	0.05	0.12	0.04	0.01
50-52	0.06	0.04	0.08	0.07	0.06	0.03	0.04	0.10	0.08	0.01	0.09	**0.04**	0.12	0.02	0.02	0.00	0.05	0.01	0.05	0.03	0.09	0.12
55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.01	0.00	0.00	0.00	0.12	0.00	0.01	0.02	0.00
60-63	0.04	0.03	0.05	0.08	0.07	0.05	0.03	0.03	0.03	0.02	0.03	0.05	0.01	**0.51**	0.07	0.00	0.00	0.10	0.02	0.12	0.00	0.01
64	0.01	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.01	0.01	0.05	0.01	0.01	**0.29**	0.05	0.04	0.03	0.02	0.03	0.04	0.02
65-71	0.06	0.13	0.03	0.05	0.06	0.03	0.03	0.03	0.05	0.11	0.07	0.29	0.17	0.09	0.12	**0.44**	0.11	0.10	0.07	0.07	0.12	0.12
72-73	0.00	0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.09	0.01	0.06	0.01	0.01	0.08	0.08	**0.30**	0.07	0.05	0.04	0.02	0.02
74	0.04	0.16	0.07	0.04	0.10	0.03	0.03	0.06	0.05	0.20	0.18	0.35	0.11	0.05	0.12	0.20	0.28	**0.23**	0.15	0.17	0.10	0.12
75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.03**	0.00	0.00	0.00
80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.02	**0.01**	0.01	0.00
85	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00	**0.10**	0.00
90-93	0.01	0.02	0.01	0.01	0.03	0.01	0.01	0.01	0.01	0.03	0.01	0.05	0.06	0.02	0.04	0.03	0.09	0.18	0.06	0.15	0.14	**0.14**

Note: For each column, the shares sum to one across all rows.

2.4.1 Paris Agreement Target and the Pan-Canadian Framework on Clean Growth and Climate Change

In 2015, Canada submitted its intended Nationally Determined Contribution to the United Nations Framework Convention on Climate Change (UNFCCC). Under the 2030 Paris Agreement, the NDC is to reduce Canada's economy-wide emissions by 30% below 2005 levels by 2030 and the 2009 Copenhagen pledge is to reduce emissions by 17% below 2005 levels by 2020. To meet the 2020 and 2030 targets, total emissions have to go down to respectively 622 and 524 Mt of CO_2. However, in 2017, economy-wide emissions were approximately 700 Mt of CO_2 and the country as a whole was not on track to achieving the target for 2030. In October 2016, the government introduced the Pan-Canadian Framework on Clean Growth and Climate Change which is proposed to ensure the implementation of a carbon constraint policy in all jurisdictions by January 2019. The framework gives local jurisdictions the flexibility to implement an explicit price-based system or a cap-and-trade system. For jurisdictions with a pricing system, the tax on carbon should reach \$50 per ton of CO_2 by 2022 and with the cap-and-trade, jurisdictions need an emissions reduction target equal to or greater than the economy-wide 30% target. The framework also states that provinces and territories will retain all revenue generated from these policies. As of November 2018, the provincial and territorial approaches to achieve these targets have still not been established for some jurisdictions. Therefore, in this section, I present the results of a policy experiment which simulates the provincial and industry-level impacts of achieving the 2030 target via the implementation of a carbon pricing system.

Canada's revised NDC submission to the UNFCCC in May 2017, states that 89 Mt of the estimated 219 Mt reduction in total emissions by 2030 will be achieved through provincial carbon pricing and federal methane regulations, 86 Mt from other regulations like the coal-phase out in electricity and clean fuel standards in transportation, and the 44 Mt from additional measures like clean infrastructure investments and carbon storage.[13] In this analysis, I investigate the impact of carbon pricing, so I consider only the targeted reduction from this regulation. Environment and Climate Change Canada (ECCC) anticipates the contribution of the proposed federal methane regulations to Canada's emissions reduction target under the Paris Agreement as 20 Mt of CO_2 equivalent.[14] The 89 Mt of estimated reduction also includes emissions reductions from international carbon credits but the amount of credits Canada is planning to use is not clear from its official submission to the UNFCCC. Therefore, roughly 69 Mt of the reduction should be achieved through carbon pricing and international carbon credits. And compared to the benchmark year of the analysis, the reduction in emissions by implementing the carbon pricing mechanisms should be equal to 66 Mt. In this section, I assume that Canada achieves this target without using any carbon credits.

The model simulation predicts that based on 2011 data, a carbon tax of $53 per ton of CO_2 is sufficient to bring Canada on track with the 2030 target. And with the proposed $50 per ton of CO_2 Canada underachieves its NDC by 3 Mt of CO_2 and probably needs international carbon credits. Holding the cost of carbon in the RoW constant, a uniform $53 per ton of CO_2 carbon tax reduces the welfare by 0.61% and the output by 0.48%. This is slightly higher than the projection of ECCC which calculates a 0.35% decrease.[15] Table 2.8 presents the impact of the increase in carbon prices on provincial welfare and emissions, and the decomposition of the change in emissions into scale, composition and technique effects. The model simulation shows that welfare falls in all regions, but the regional impacts vary. The smallest decrease is in Quebec with 0.004%. Alberta faces the largest fall in welfare

[13] See "Canada's 2017 Nationally Determined Contribution Submission to the United Nations Framework Convention on Climate Change".

[14] See the "technical backgrounder" for the proposed federal methane regulations for the oil and gas industry, ECCC, 2017.

[15] ECCC projects that "in 2022, the measures in the Pan-Canadian Framework, including carbon pricing but excluding infrastructure investments and technology incentives, will reduce the level of GDP by about 0.35%." See the Economic Analysis of the Pan-Canadian Framework, ECCC, 2017.

with almost a 2% decrease in welfare and is followed by Nova Scotia with a 1.3% decrease. Other provinces are all around or below the Canadian average. The decreases in output levels mirror the fall in welfare. Emissions decrease in all regions and slightly increase in the RoW. On average industrial emissions in Canada decrease by 17.27%. The decomposition indicates that the change in emissions is largely explained by the technique effect. Therefore, emission intensities decrease in all regions. There is heterogeneity across provinces in terms of the initial implicit carbon costs (determined by the cost of fossil fuel inputs). Regions with relatively high initial carbon prices see relatively small increases in carbon prices and the corresponding technique effects are small as well. In provinces like Alberta, Saskatchewan and Nova Scotia[16] where fossil fuels are relatively inexpensive compared to the rest of Canada, the implicit cost of carbon emissions are low and therefore, an extra charge of carbon tax matters more.

A small fraction of the total change in emissions is explained by the scale and composition effects. There is a small but positive scale effect in Quebec, this is due to the reshuffling of inputs across industries in the province. Although the aggregate output level decreases, the cost of production in some industries like the machinery and equipment production slightly falls due to the decrease in provincial wage rate which ultimately decreases the consumer price index in Quebec by 0.05% and results in a small positive scale effect. The increase in the cost of carbon contracts the economic activity in other regions to a small extent and this contributes to the decrease in emissions. The small but positive composition effects in Manitoba, Yukon and Prince Edward Island is a result of the high initial implicit carbon prices. The percentage changes in the cost of carbon in these regions are relatively small, therefore the incentive to shift production towards cleaner industries is relatively low.

[16]The Dartmouth Refinery in Nova Scotia closed in 2013, this change is not reflected in the data used in this paper. Accounting for that may have an upward pressure on the implicit cost of carbon in Nova Scotia in the baseline equilibrium.

Table 2.8: Percentage Change in Welfare, Output and Emissions, by Region

Region	Welfare	Output	Emissions	Scale	Composition	Technique
AB	-1.98%	-1.35%	-22.53%	-1.83%	-0.73%	-19.97%
BC	-0.45%	-0.29%	-13.83%	-0.43%	-0.34%	-13.06%
MB	-0.38%	-0.16%	-9.28%	-0.40%	0.25%	-9.13%
NB	-0.61%	-1.22%	-18.75%	-1.31%	-0.60%	-16.83%
NL	-0.38%	-0.16%	-10.97%	-0.38%	-0.05%	-10.54%
NS	-1.27%	-1.71%	-22.99%	-2.02%	-0.94%	-20.14%
ON	-0.28%	-0.28%	-15.46%	-0.29%	-0.54%	-14.63%
PE	-0.76%	-0.59%	-7.79%	-1.02%	0.18%	-6.94%
QC	-0.00%	-0.02%	-10.94%	0.03%	-0.13%	-10.84%
SK	-0.35%	-0.38%	-21.58%	-0.27%	-0.17%	-21.14%
YT	-0.07%	-0.05%	-5.70%	-0.10%	0.27%	-5.88%
Canada	-0.61%	-0.48%	-17.27%	-0.65%	2.86%	-20.28%
RoW	0.35%	0.34%	0.18%	0.37%	0.01%	-0.03%

Note: Displays the percentage changes in welfare, output and emissions, also provides the decomposition of the change in emissions into scale, composition and technique effects. The three effects sum up to the total change in emissions.

The aggregate effect on output seems small in magnitude but there are wide variations across regions and industries. Table 2.9 shows the the percentage changes in industrial outputs by region. The largest impact of the increase in the cost of carbon emissions is seen in the emission intensive industries like chemicals. Emission intensive petroleum refining, and cement and concrete production are categorized under the chemicals industry. With its large oil and gas industry, Alberta's chemicals output shrinks by 8.9%. But the output of mining which is the other large and emission intensive industry in Alberta, falls by a small 0.4%. The reason for this is the change in input use. Chemicals industry is a substantial employer in Alberta. The substantial decrease in chemicals output releases labour into the market which is mobile across industries but not across regions. This lowers wages and since the emission intensity of mining is less than chemicals in Alberta, as the biggest employer in the province, the mining industry, benefits from it. While Alberta's mining and chemicals outputs decrease, outputs of these industries increase in Manitoba even though these are also the most emission intensive industries in the province. Manitoba's mining industry has the lowest emission intensity among all provinces, as output from Alberta decreases, Manitoba satisfies the demand and Manitoba's mining exports to all other regions increase as a result. Another example is the British Columbia's chemicals industry with its 2% expansion in output. Inter-industrial linkages are behind this change. Looking at the changes in output on Table 2.9 and exports on Table 2.11 together, one can see that Alberta's mining output slightly decreases while its mining exports increase. On the other hand, British Columbia's mining output and exports decrease while they increase for its chemicals industry. As explained before, the small decrease in the output of Alberta's emission intensive mining industry is due to the effect of the release of labour from the chemicals industry on the cost of production in other industries. The largest consumer of mining output in Alberta is the chemicals industry, but domestic consumption of mining products decrease as the chemicals industry shrinks. Therefore, some part of this mining output is exported to British Columbia since the relative increase in prices are lower in Alberta and British Columbia's chemical production and exports increase. Therefore, the adjustments through inter-industry linkages and interprovincial trade have a significant role in propagating the effect of carbon taxes to the whole economy. The high percentage changes in small regions like Yukon and Prince Edward Island should be noted. The reason for this is how the results are presented. Ontario is the largest exporter and producer of chemicals in Canada and these are percentage changes from the initial equilibrium. On the other hand, there are two establishments in Yukon producing a small amount of chemicals but at a relatively low emission intensity. Therefore, even small changes in output can generate high percentage changes depending on the size of the regional economy. The effect of the large share of coal used in power generation in Nova Scotia can also be seen on this table, the output of the utilities in the province falls by 2.2%. Agriculture and forestry is another industry that shrinks substantially in most regions. Among large producers of manufacturing goods, on average, the smallest decrease in output is in British Columbia. Interprovincial exports of manufacturing goods also increase in British Columbia. This is partly due to the low emission intensity in manufacturing production in the province.

As presented on Table 2.10, the percentage decreases in emissions are significantly larger than the decreases in output for all regions. This is, in large part, due to the decrease in emission intensity in all industries. The largest decreases in emissions are in the manufacturing industries. More specifically, chemicals, wood, food and textiles, and machinery and equipment industries are the largest contributors in manufacturing to the decrease in emissions. Transportation is another one which is not traded as much and quite emissions intensive, therefore, the magnitude of decrease in transportation emissions is large in all regions. The increase in the cost of carbon doesn't affect all provinces equally, British Columbia has a relatively less emission intensive manufacturing industry, this is evident in the percentage changes in emissions in the province. While chemicals production increases by 2.1% in British Columbia, emissions decrease by 10.5%. Technique effect explains this decrease in emissions. While output increases, the reallocation of inputs makes the decrease in emissions possible.

Table 2.9: Percentage Change in Output, by Industry and Region

Industry	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK	YT
Agriculture and Forestry	-1.6	-1.6	0.1	-3.5	-0.8	-1.0	-0.6	-0.5	-0.1	-0.5	-0.9
Mining	-0.4	-0.2	0.4	-0.1	0.0	-4.0	-0.4	-5.4	-1.7	0.1	0.3
Food and Textiles	-1.9	-0.3	-0.4	-0.4	-0.1	-1.4	0.2	-1.3	-0.3	-0.2	-0.5
Wood	-1.0	-0.0	-0.2	0.1	0.4	-9.2	0.3	-2.0	0.2	0.7	0.5
Paper	-0.1	-0.1	-0.7	-1.6	0.3	-1.8	0.3	-1.8	0.5	-0.4	0.2
Chemicals	-8.2	2.1	1.1	-4.7	-0.8	-8.9	-2.3	3.1	0.1	-1.9	7.3
Metals	-0.7	-0.2	-0.1	-1.3	-0.7	-1.7	-0.7	-1.9	0.1	-0.8	0.2
Machinery and Equipment	-1.8	-0.3	-0.6	-0.9	-0.3	-0.0	0.6	-3.7	0.6	-0.5	-0.3
Manufacturing, n.e.c.	0.4	0.5	0.2	0.3	-0.4	-1.0	0.7	-1.0	0.4	0.3	-0.6
Utilities	-2.2	-0.2	-0.0	-2.4	-0.2	-2.2	-0.3	6.0	0.1	-0.6	-0.1
Construction	-1.4	-0.3	-0.2	-0.5	-0.2	-1.0	-0.2	-0.5	-0.1	-0.4	-0.0
Wholesale and Retail	-1.0	-0.3	-0.4	-0.0	-0.3	-0.4	-0.2	-0.2	-0.1	-0.8	-0.5
Hotels and Restaurants	-0.5	-0.1	-0.3	0.1	-0.3	-0.5	0.0	-0.7	0.0	-0.5	-0.4
Transportation	-1.7	-0.9	0.3	-0.2	-0.1	-3.5	-1.4	0.2	-0.2	-1.0	0.9
Communication	-0.5	-0.3	-0.3	-0.2	0.1	-0.1	-0.3	0.0	0.0	-0.9	-0.1
Finance	-0.8	-0.3	-0.3	-0.3	-0.3	-0.6	-0.2	-0.4	-0.1	-0.5	-0.3
Computer and Related Activities	0.6	-0.2	-0.9	0.6	-0.3	2.1	0.2	-0.0	0.0	-0.6	-1.1
Other Business Activities	-0.5	-0.3	-0.7	-0.3	-0.5	-0.7	-0.1	-0.9	0.0	-0.6	-0.4
Public Administration	-1.5	-0.3	-0.1	-0.5	-0.2	-1.0	-0.3	-0.3	-0.0	-0.5	-0.0
Education	-1.4	-0.3	-0.1	-0.5	-0.2	-0.8	-0.2	-0.3	-0.0	-0.5	-0.1
Health and Social	-1.5	-0.3	-0.2	-0.5	-0.2	-0.9	-0.3	-0.4	-0.1	-0.5	-0.2
Other Services	-1.0	-0.3	-0.3	-0.3	-0.3	-0.9	-0.1	-0.7	0.0	-0.4	-0.1

[]Note: Displays the percentage changes in output by industry and region.

Table 2.10: Percentage Change in Emissions, by Industry and Region

Industry	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK	YT
Agriculture and Forestry	-19.8	-13.8	-8.9	-18.5	-10.9	-19.3	-14.1	-7.5	-10.3	-19.4	-6.6
Mining	-18.8	-12.5	-8.6	-15.7	-10.2	-21.6	-14.0	-12.1	-11.7	-18.9	-5.4
Food and Textiles	-20.0	-12.6	-9.3	-15.9	-10.3	-19.5	-13.5	-8.3	-10.5	-19.1	-6.2
Wood	-19.3	-12.4	-9.1	-15.5	-9.9	-25.9	-13.4	-9.0	-10.1	-18.4	-5.3
Paper	-18.6	-12.4	-9.5	-16.9	-9.9	-19.9	-13.3	-8.8	-9.8	-19.3	-5.5
Chemicals	-25.2	-10.5	-7.9	-19.5	-11.0	-25.7	-15.6	-4.2	-10.2	-20.5	1.1
Metals	-19.1	-12.5	-9.0	-16.7	-10.8	-19.8	-14.3	-8.9	-10.2	-19.6	-5.6
Machinery and Equipment	-19.9	-12.6	-9.5	-16.3	-10.5	-18.4	-13.1	-10.6	-9.7	-19.4	-6.1
Manufacturing, n.e.c.	-18.2	-11.9	-8.8	-15.3	-10.5	-19.2	-13.0	-8.1	-9.9	-18.7	-6.3
Utilities	-20.3	-12.5	-8.9	-17.6	-10.4	-20.2	-13.9	-1.6	-10.1	-19.5	-5.8
Construction	-19.7	-12.6	-9.1	-16.0	-10.4	-19.2	-13.8	-7.5	-10.3	-19.3	-5.8
Wholesale and Retail	-19.3	-12.7	-9.3	-15.6	-10.5	-18.7	-13.8	-7.3	-10.3	-19.6	-6.3
Hotels and Restaurants	-18.9	-12.4	-9.3	-15.5	-10.4	-18.8	-13.6	-7.8	-10.2	-19.4	-6.1
Transportation	-19.9	-13.1	-8.6	-15.8	-10.3	-21.3	-14.9	-6.9	-10.4	-19.8	-4.9
Communication	-18.9	-12.6	-9.2	-15.7	-10.1	-18.5	-13.9	-7.1	-10.3	-19.7	-5.9
Finance	-19.2	-12.6	-9.2	-15.8	-10.5	-18.9	-13.8	-7.5	-10.3	-19.4	-6.1
Computer and Related Activities	-18.0	-12.5	-9.7	-15.1	-10.5	-16.7	-13.4	-7.1	-10.2	-19.4	-6.8
Other Business Activities	-18.9	-12.6	-9.6	-15.8	-10.6	-18.9	-13.7	-7.9	-10.2	-19.5	-6.2
Public Administration	-19.7	-12.6	-9.1	-16.0	-10.3	-19.2	-13.8	-7.4	-10.3	-19.3	-5.8
Education	-19.6	-12.6	-9.1	-16.0	-10.4	-19.1	-13.8	-7.4	-10.3	-19.3	-5.9
Health and Social	-19.7	-12.6	-9.1	-16.0	-10.4	-19.2	-13.8	-7.4	-10.3	-19.3	-5.9
Other Services	-19.3	-12.6	-9.2	-15.8	-10.4	-19.1	-13.7	-7.7	-10.2	-19.3	-5.9

Note: Displays the percentage changes in emissions by industry and region.

The change in the cost of emissions induces a change in the relative prices in the economy and ultimately leads to changes in trade patterns. Table 2.11 displays the percentage changes in exports by industry and region. Total exports fall but there are large differences across industries and regions. When the inter-industrial linkages are not present, changes in trade flows follow closely the changes in prices which arise as a direct consequence of the carbon tax. On the other hand, when inter-industrial linkages are present, firms can substitute between primary and intermediate inputs and look for the lowest cost suppliers of intermediate goods. Then, the counterfactual trade flows and the price levels that determine these trade patterns are affected together by the cost of carbon and the cost of intermediate inputs, therefore they are determined by the general equilibrium effects. Price levels may or may not increase depending on the cost of primary inputs and the changes in the cost of intermediate input mix. A direct consequence of these relative price differences is the change in trade patterns. One example is Alberta's chemicals industry. The increase in the cost of carbon negatively affects the competitiveness of the chemicals industry in Alberta. The average cost of production in Alberta's chemicals industry increases by 1.15% in response to the increase in cost of carbon. This is the largest increase across all regions. Indeed, chemicals exports from Alberta decrease by roughly 7%, imports and domestic consumption also decrease respectively by 2.68% and 9.2% which indicate a contraction in the industry. Ontario with its relatively low cost of primary factors and intermediate inputs, increases its exports of manufacturing goods and especially of machinery and equipments.

Table 2.11: Percentage Change in Exports, by Industry and Region

Industry	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK	YT
Agriculture and Forestry	-0.490	-1.502	0.140	-3.201	-0.940	-0.241	-0.561	-0.196	-0.004	-0.418	-0.991
Mining	0.333	-0.221	0.445	0.458	0.009	-3.112	-0.129	-5.364	-1.623	0.224	0.350
Food and Textiles	-1.476	-0.325	-0.353	-0.258	0.027	-1.069	0.237	-1.176	-0.299	-0.144	-0.692
Wood	-0.412	0.061	-0.159	0.209	-0.860	-8.410	0.465	-1.846	0.145	0.783	0.578
Paper	0.636	0.077	-0.548	-1.303	0.427	-1.320	0.428	-1.631	0.508	-0.116	0.238
Chemicals	-7.106	2.011	1.048	-4.527	-0.741	-7.754	-1.906	3.021	-0.081	-2.024	7.173
Metals	0.157	-0.078	-0.009	-1.156	-0.875	-1.330	-0.605	-1.272	0.059	-0.914	0.505
Machinery and Equipment	-0.697	-0.028	-0.487	-0.560	-0.090	0.640	0.725	-3.226	0.642	-0.376	-0.372
Manufacturing, n.e.c.	1.011	0.588	0.257	0.501	-0.380	-0.391	0.739	-0.828	0.396	0.295	-0.441
Utilities	-0.728	-0.512	0.310	-1.895	-0.365	-0.169	0.112	5.758	0.251	-1.692	0.340
Construction	-0.235	-0.289	-0.429	-0.131	-0.765	-0.286	-0.227	-0.572	-0.063	-0.449	-0.447
Wholesale and Retail	0.116	-0.365	-0.396	0.452	-0.141	0.559	-0.054	0.016	-0.150	-0.525	-0.699
Hotels and Restaurants	0.400	-0.024	-0.373	0.239	-0.271	-0.066	0.301	-0.676	0.105	-0.501	-0.376
Transportation	-0.680	-0.793	0.129	-0.058	-0.283	-2.345	-1.191	0.215	-0.346	-0.798	0.747
Communication	0.330	-0.249	-0.325	0.096	0.209	0.637	-0.367	0.245	-0.155	-0.555	-0.244
Finance	0.156	-0.205	-0.485	-0.127	-0.349	0.211	-0.320	-0.267	-0.356	-0.368	-0.579
Computer and Related Activities	1.226	-0.152	-0.901	0.710	-0.240	2.317	0.259	-0.047	-0.026	-0.590	-1.115
Other Business Activities	0.208	-0.371	-0.691	-0.220	-0.604	0.216	-0.063	-0.979	-0.010	-0.783	-0.181
Public Administration	0.340	0.340	0.340	0.340	0.339	0.340	0.340	0.339	0.340	0.340	0.339
Education	0.015	0.135	-0.016	-0.152	-0.166	-0.108	0.010	0.096	0.131	-0.145	0.123
Health and Social	-0.189	-0.690	-0.447	-0.216	-0.034	-0.279	-0.334	-0.020	-0.293	-0.538	-0.408
Other Services	-0.041	-0.233	-0.269	-0.190	-0.286	-0.116	-0.006	-0.567	-0.052	-0.340	-0.212

Note: Displays the percentage changes in total exports by industry and region.

Table 2.12: Percentage Change Emissions Content of Bilateral Trade, by Region

	AB	BC	MB	NB	NL	NS	ON	PE	QC	RoW	SK	YT
AB	-	7.24	12.52	1.70	10.21	-2.56	5.63	14.47	10.64	23.03	-0.81	17.27
BC	-9.79	-	4.54	-3.75	2.66	-9.90	-1.77	6.36	2.62	14.55	-7.87	8.61
MB	-14.26	-4.22	-	-8.33	-1.29	-12.80	-5.90	2.18	-1.75	9.65	-11.80	3.87
NB	-4.40	4.66	9.47	-	5.30	-4.23	2.85	11.70	7.51	17.15	-3.58	13.78
NL	-10.72	-2.62	1.70	-7.66	-	-12.27	-4.40	3.08	-0.15	11.24	-10.17	5.95
NS	-2.16	7.64	12.45	1.75	9.53	-	5.72	14.72	10.55	21.79	-0.27	17.05
ON	-6.87	1.33	6.14	-2.65	4.33	-7.47	-	7.99	4.06	16.16	-6.36	9.98
PE	-12.97	-5.99	-1.58	-11.05	-3.46	-14.04	-7.59	-	-3.45	7.31	-13.52	2.47
QC	-10.47	-2.64	1.89	-8.01	0.24	-11.59	-4.25	3.50	-	11.60	-10.12	5.74
RoW	-19.06	-12.67	-8.68	-17.81	-10.18	-20.82	-14.35	-7.37	-10.52	-	-19.19	-5.39
SK	-1.66	7.70	12.84	4.07	10.90	-2.37	5.95	15.09	10.72	23.48	-	16.74
YT	-15.97	-7.43	-3.48	-13.15	-4.81	-15.86	-8.99	-1.98	-4.92	5.88	-14.30	-

Note: Displays the percentage change in the emissions embodied in the imports of the row region from the column region.

With the increase in the cost of emissions, both interprovincial and international trade patterns change in terms of the total amount of goods traded, composition of the goods traded and the emission intensity of the goods traded. All these three factors work together in determining the net change in the emissions content of trade. Table 2.12 summarizes average changes in emissions content of bilateral trade. Changes due to demand for domestic production are excluded. Alberta's total amount of imports decrease in all industries but the emission content of its imports increase. This is due to the decrease in domestic production in emission intensive industries, the demand for these goods is satisfied by imports. Provinces import between 6 and 24% more emissions embodied in trade from the RoW. On average, emissions content of exports to the RoW falls at a smaller degree, and the net emission imports into Canada rises. This indicates the emission relocation outside Canada.

The predicted emission relocation into the RoW is 10.8%. There is no literature that assesses the possible extent of carbon leakage from the NDCs under the Paris Agreement but previous research by Aichele (2013) on carbon leakage from the commitments under the Kyoto Protocol finds emission relocation rates between 2 and 10% across regions and more specifically a 9.9% carbon leakage into the RoW if Canada were to satisfy its Kyoto commitment.

2.4.2 The Role of Output-Based Pricing System

In addition to the carbon tax applied on combustion emissions, the federal carbon pricing backstop also outlines an Output-Based Pricing System (OBPS) for industrial facilities. The OBPS allows regulated facilities to be subject to the carbon tax on the portion of their emissions that exceeds an annually determined output-based emissions limit, therefore it provides free emission allocations to regulated facilities. The aim of the OBPS is to reduce competitiveness pressures and carbon leakage.[17] Output-based subsidies create an incentive

[17]Details on the OBPS are provided in Government of Canada (2018b).

for firms to produce more, offset part of the upward pressure on prices induced by the carbon tax, and hence reduce shifts in output created by differences in regulatory stringency across regions. In this section, using the same general equlibrium model, I examine the effect of the OBPS in reducing the carbon leakage.

For this analysis, I rely on the overview provided in the report published by the Government of Canada in January 2018 (Government of Canada, 2018a).[18] The annual emissions limit of a regulated facility is determined by multiplying the applicable output-based standard and the facility's total annual output. And the corresponding compliance obligation is then equal to the total annual facility emissions minus its annual emissions limit.[19] Facilities with emissions above the annual limit may pay the carbon tax on the excess emissions, submit offset credits or surplus credits issued by the federal government to meet their obligations. I assume that the carbon tax is the only option available in the economy. At this stage, the OBPS is introduced for oil and gas, pulp and paper, chemicals, nitrogen-fertilizers, lime, cement, base metal smelting and refining, potash, iron ore palletizing, mining, iron and steel, and food processing. Since the data in this paper don't exactly match the categories announced by the government, I assume the OBPS applies to all manufacturing industries. The proposed starting percentage by the government for all output-based standards was 70% of the production-weighted national average of emission intensity.[20] To find total carbon leakage under the two components of the federal carbon pricing backstop (the carbon tax and the OBPS), I determine the annual emissions limit as the 70% of the emissions intensity of industry j (calculated as the total emissions of industry j divided by the total production

[18]Although the OBPS and the Carbon Competitiveness Incentive Regulation (CCIR) introduced by the Government of Alberta currently have different coverages, the ECCC approves that the system in Alberta meets the federal benchmark. Here, I assume that all provinces are regulated under the OBPS. For a more complete discussion on provincial emissions coverage, see Dobson et al. (2018).

[19]Since the data is at the industry level, it is not possible to perform this analysis at the facility level, this is a serious restriction, therefore, the numbers provided in this section should be considered as the results of an hypothetical exercise with an aim of giving the approximate direction in the change in carbon leakage.

[20]The specific details of the regulation on the OBPS were later released by the ECCC in December 2018, for details see (Government of Canada, 2018b).

of j across all regions) multiplied by total production. The annual emissions limit is then equal to the amount of emissions the industry gets allocated for free and the carbon tax is applied on the portion that exceeds the limit. The results show that under the OBPS, the carbon leakage is reduced by 1.43% compared to the previous case with carbon taxes.

2.5 Conclusion

The purpose of this paper is to develop an understanding of how the effects of the proposed changes in carbon policy are transmitted through the Canadian economy. I employ a multi-industry Ricardian trade model with input-output linkages calibrated to the Canadian economy disaggregated across industries and provinces. The theoretical model employed in this paper allows me to quantify the welfare, trade and emissions effects and the extent of carbon leakage taking the general equilibrium effects into account.

The model predicts that a carbon tax of \$53 per ton of CO_2 is sufficient to bring Canada on track with its NDC under the Paris Agreement. This leads to a small reduction in aggregate welfare by 0.61% and a 0.48% decrease in output. The counterfactual analysis presents a detailed assessment of the impacts for each province since the model takes inter-industrial adjustments and the adjustments through interregional trade into account and aims to inform the policy. The decreases in industry emissions are mostly due to decreases in emission intensity of production (technique effect) and not due to decreases in output (scale effect).

Meeting the NDC leads to a 10.8% of emission relocation out of Canada. Provincial governments suggest certain policy alternatives to protect their EITE industries and reduce carbon leakage (like the output-based allocations in Alberta). The OBPS introduced by the federal carbon pricing backstop reduces the carbon leakage from Canada by 1.43%.

The emissions embodied in interregional trade flows also change significantly. The trade responses to carbon policy does not always favour the provinces with the cleanest production technologies since trade costs affect the counterfactual results together with the emission intensity of production. For example, Manitoba experiences an increase in agricultural exports even though its emission intensity in agriculture is relatively high compared to most provinces. Adjustments through input demand are also important in determining the EITE industries. Mining in Alberta is considered as one of them, but the exports of this industry increases in the counterfactual equilibrium since the decrease in output of the chemicals industry releases labour which decreases the average wage rate in the province and results in an increase in the mining exports. Therefore, general equilibrium effects are important in determining heterogeneous impacts on bilateral trade flows and industry output.

Chapter 3

Optimal Carbon Tariffs, Retaliation and Trade Wars in the Paris Agreement

3.1 Introduction

Voluntary participation in global emission reduction efforts creates a non-cooperative policy environment where participating countries, motivated by both economic and environmental concerns, consider trade restrictions such as carbon tariffs. Carbon tariffs have been suggested as an enforcement mechanism that can eliminate the problem of free riding. However, if non-participating countries are not better off by cooperating under the presence of carbon tariffs, there are concerns that they may retaliate and this may spark a trade war among countries with different levels of environmental policy stringency. In light of the debates around the Paris Agreement, in this paper, I examine whether carbon tariffs can be effectively adopted to encourage cooperation among all parties.

The international agreement adopted in 2015 at the 21st Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) created optimistic expectations for cooperation in international climate policy since both industrialized and developing countries agreed to reduce greenhouse gas emissions (GHG) via voluntary pledges to keep the global mean surface temperature less than 2 degrees Celsius above pre-industrial levels. However, the announcement of the United States, the world's largest economy and the second largest emitter,[1] to withdraw from the agreement created the need to assess the effect of this withdrawal on the compliance prospects of the agreement, and raised the question how other countries should respond. Following the announcement of the US withdrawal, punitive measures, like carbon tariffs have gained supporters among the ratifying parties of the Paris Agreement as an action against non-action.[2] With mechanisms well documented in the literature, when parties do not make commitments comparable with each other on GHG emission reductions, carbon leakage, the reshuffling of emissions to non-regulated regions, can reduce the effectiveness of policies in place. As an alternative to globally coordinated measures, carbon tariffs, although complicated and costly to design and implement, can limit this increase in emissions by shifting part of the economic burden to the unregulated regions.[3]

Although the environmental and economic effects of alternative carbon tariff designs have been studied in detail in the literature, due to computational and methodological constraints, there are fewer examples that analyse environmental regulations in an optimal policy framework. In particular, previous quantitative analyses mainly focus on carrying out comparative statics of environmental policy alternatives and policy formation among coalition and non-coalition countries. In the current policy environment, mitigation measures adopted across countries are strongly asymmetric. Countries participating in the Paris Agreement determine their emission reduction rates voluntarily and there is no mechanism in the agreement to enforce participation or commitment. For countries that consider

[1] See Boden et al. (2017) for an analysis of how countries compare in terms of total emissions.

[2] "If Trump wants to withdraw the US from the Paris climate agreement, the rest of the world should impose a carbon-adjustment tax on US exports that do not comply with global standards." J.E. Stiglitz, The Guardian, June 2017. "Further work on developing carbon border adjustments is necessary as a leverage for further efforts by all countries to achieve the objectives enshrined in the Paris Agreement." European Parliament resolution of 3 July 2018 on climate diplomacy. See also Kemp (2017)

[3] Fischer et al. (2009) and Frankel and Aldy (2009) review the legal barriers to implementing carbon tariffs based on carbon content of imports. Böhringer et al. (2012) consider alternative designs for anti-leakage measures and compares them in terms of cost effectiveness.

relatively aggressive carbon pricing, this non-cooperative policy formation amplifies the fear for their competitive position in the world economy. Since carbon pricing as a policy instrument cannot be optimally deployed in a cooperative setting under these circumstances, carbon tariffs emerge as a second-best instrument that might have a role to address these environmental challenges. Therefore, a detailed exploration of the strategic interactions between countries and the roles of trade and environmental policies in these interactions is necessary.

To do this, I build on the theoretical framework of Ossa (2014). In section 3.2, I present a multi-industrial, multi-regional general equilibrium trade model with emission externalities from production. The model provides a comprehensive and flexible framework that can be used to analyse optimal environmental and trade policies in a multi-industry and multi-region set up and allows me to measure non-cooperative optimal policy choices at the industry-level for each country. I then analyse the resulting strategic interactions between countries. I investigate these interactions between trade and environmental policies and the implications of these interactions in the non-cooperative policy environment in light of the debates around the withdrawal of the US from Paris Agreement.

In response to the US withdrawal, participating may choose to impose carbon tariffs on the US imports to encourage cooperation. Therefore, the first step of the analysis is to answer the following question: What are the optimal carbon tariffs in the presence of an unbinding environmental agreement where parties unilaterally decide their abatement levels? I also investigate how the resulting optimal carbon tariffs depend on different economic variables like trade elasticities and trade exposure levels. However, optimal carbon tariffs can be effectively adopted when imposing countries do not expect retaliation. The US may be better off by taking retaliatory action in the form of a more protectionist trade policy against the countries that impose carbon tariffs on its imports. If other countries decide to respond to the US retaliation, this may lead to a worldwide trade war among all parties. What are the environmental and economic consequences for both participating and non-participating countries if carbon tariffs lead to a trade war? Focusing on the role of carbon tariffs, I study these strategic interactions across five regions, Canada, China, the European Union, the United States and a constructed rest of the world.

I find that carbon tariffs imposed by the ratifying regions on US imports are successful in restricting emissions from US production but the US is better off when it withdraws from the agreement and faces the carbon tariffs rather than striving to achieve its Paris Agreement target. Imposing regions gain from carbon tariffs, both in terms of environmental outcomes and improved terms of trade, but carbon tariffs are not successful in enticing the US to restrict its emissions and capture the revenues otherwise accruing to its trade partners. The results of the retaliation scenario show that the US would prefer imposing import tariffs on exports of other countries in response to carbon tariffs. However, a tariff war in response to US retaliation is not likely. Under a possible worldwide tariff war scenario, all regions take protectionist measures and increase their import tariffs. These are Nash equilibrium tariffs. They substantially differ across countries and industries emphasizing the role of trade elasticities. The results show that a tariff war induced by the US retaliation leaves all countries worse off compared to the Paris Agreement scenario indicating that when faced with the threat of a tariff war, the best play for all countries, including the US, is to meet their Paris Agreement pledges.

The legality of carbon tariffs is still debated, compatibility of such border measures to World Trade Organization (WTO) rules is often defended based on the environmental conservation and public health exceptions outlined in the Article XX of the General Agreement on Tariffs and Trade (GATT).[4] Of particular relevance to the legal debate is also the

[4]See for example Nordhaus (2015).

fundamental requirement of the WTO which states that for a particular environmental policy to be acceptable under the GATT disciplines, it must not lead to unjustifiable discrimination between countries.[5] When analysing the effects of carbon tariffs, the literature generally resorts to a standard approach of calculating carbon tariffs that is most likely to satisfy the regulatory exceptions of the GATT. This involves eliminating the burden on domestic production imposed by environmental tax differentials between countries and imposing tariffs on embodied emissions in imports calculated without discriminating trade partners based on process and production methods. After presenting the results of the benchmark scenario where all ratifying regions including the US achieve their targets as agreed in the Paris Agreement, and also the effects of the US withdrawal, for GATT consistency, I calculate the "standard" carbon tariffs which are equal to the carbon tax that would have been imposed had the good been produced in the importing region (therefore, based on the emission intensity of the importer). This exercise shows that the carbon tariffs calculated based on the domestic emission cost differences across countries are substantially lower than the optimal carbon tariffs. This is a confirmation of the previous theoretical literature: Countries have motivation to influence the terms of trade in their favour and set carbon tariffs higher than the environmentally optimal levels.

There are numerous studies investigating the effects of exogenously determined carbon tariffs on carbon leakage, welfare and competitiveness. Condon and Ignaciuk (2013) provide an extensive review of the early literature on carbon tariffs. The main findings of this literature are that carbon tariffs reduce carbon leakage, shift the cost of abatement partly from high carbon tax countries to low carbon tax countries, and reduce competitiveness pressures on emission-intensive and trade-exposed industries in high carbon tax countries. Among the large number of studies that evaluate the efficiency and effectiveness of various carbon tariff designs imposed by a coalition of high carbon tax countries to low carbon tax

[5]For more information on this subject, see GATT Article XX on General Exceptions.

countries, several incorporate carbon tariffs to existing environmental policy schemes, for example Babiker and Rutherford (2005) show that carbon tariffs can reduce the negative welfare effects on the Kyoto coalition countries by shifting the cost of abatement partly to the non-coalition countries. Using a partial equilibrium model, Monjon and Quirion (2011) investigate whether carbon tariffs can address the competitiveness concerns of the the emission intensive industries regulated under the EU-ETS. A recent example is the work of Larch and Wanner (2017) who find that incorporating carbon tariffs increase the effectiveness of the Copenhagen Accord by lowering carbon leakage. The theoretical literature on optimal environmental tariffs begins with Markusen (1975) who, although not specifically focusing on carbon tariffs, establishes the optimal domestic and trade policy instruments in a two-good, two-country neoclassical general equilibrium model with cross-border production externalities. He shows that import tariffs can be a tool for a sufficiently large coalition of countries to control the externality from foreign production. Building on the analysis of Markusen (1975), Hoel (1996) examines the optimal unilateral carbon taxes in a non-cooperative setting and the corresponding level of import tariffs as a policy response. The main conclusions of his analysis are that optimal carbon taxes should not be differentiated across industries provided that countries are not prevented from using import tariffs as an instrument and that the optimal tariffs must approach zero as international market power approaches zero. The majority of the studies on optimal environmental policy is based on the theoretical framework established by Hoel (1996). And the literature focusing on the optimal carbon tariffs and the quantitative analysis of strategic interactions between countries is relatively recent. Based on the model framework developed by Markusen (1975), Balistreri et al. (2016) study the optimal carbon tariffs imposed by a coalition formed by the Annex I countries on imports from the non-coalition countries in two emission intensive industries. They find that optimal carbon tariffs that arise only from environmental concerns of the coalition is substantially lower than the level of coalition carbon tax. Employing a CGE model, Böhringer and Rutherford (2017), examine the effect of exogenous carbon tariffs imposed on the US after its withdrawal from the Paris Agreement and calculates the retaliating optimal import tariffs as a strategic response by the US on the rest of the world. Similar to the results presented in this paper, Böhringer and Rutherford (2017) find that carbon tariffs do not pose a credible threat to the US and it is better of withdrawing from the agreement. Winchester (2018) studies the same subject and analyses whether carbon tariffs can be used to enforce participation in the Paris Agreement. The results are similar, although carbon tariffs result in small reductions in the US emissions and welfare levels and is better off when it does not restrict emissions and faces the carbon tariffs.

The remainder of the paper is organized as follows. Section 3.2 presents the basic setup of the model. Section 3.3 describes the data and the calibration of the model parameters. Section 3.4 shows the effects of achieving the emission reduction targets adopted by the countries in the Paris Agreement, the consequences of the US withdrawal, then calculates and evaluates the optimal carbon tariffs, finally discusses the implications of retaliation and a worldwide tariff war. The last section concludes.

3.2 A Quantitative Framework for Optimal Tariffs with Pollution Externalities

I start by outlining a static general equilibrium model of international trade that incorporates emissions from production. The model is then used to analyse the outcome of how economies respond to strategically determined policy interventions that control pollution emissions. The model embeds a variant of other gravity models comprehensively surveyed in Costinot and Rodríguez-Clare (2014) and provides a rich and flexible general equilibrium framework to explore optimal environmental policy alternatives. The setup of the model is based on the theoretical foundation introduced by Ossa (2014) which features imperfect competition and firms differentiated in productivity levels, but builds on it to reflect stylized properties of polluting industries. Specifically, pollution is an increasing function of output and a decreasing function of pollution abatement expenditures, and productivity levels determine pollution intensity of production. All productive processes generate some pollution and firms invest in abatement technologies in response to the stringency of environmental policy. The model serves to introduce a quantitative analysis of optimal carbon tariffs in the presence of pollution externalities in a multi-regional and multi-industrial framework.

The model describes a world of N regions indexed by i and j, and S industries indexed by s. Each region is endowed with a fixed labour force L_i. In each region, consumers have access to a continuum of varieties differentiated by their productivity levels and consumer preferences over these varieties follow a utility function given by

$$U_j = \prod_{s=1}^{S} \left[\left(\sum_{i=1}^{N} \int_0^{M_{is}} x_{ijs}(\nu_{is})^{\frac{\sigma_s - 1}{\sigma_s}} d\nu_{is} \right)^{\frac{\sigma_s}{\sigma_s - 1}} \right]^{\mu_{js}} \left[\frac{1}{1 + \left(\eta_j^{-1} \sum_{i=1}^{N} Z_i \right)^2} \right] \tag{3.1}$$

Equation (3.1) describes the nested utility function of consumers in region j with Cobb-Douglas preferences across industries and constant elasticity of substitution (CES) preferences across product varieties within an industry s. All income from wages and pollution control regulations accrues to the consumers and is allocated across varieties of goods, ν_{is}, from the mass M_{is} of industry s varieties produced in region i. $x_{ijs}(\nu_{is})$ represents the quantity of variety ν_{is} goods in industry s exported from region i to j. The share of region j's income spent on industry s varieties is given by μ_{js}, where $\sum_{s=1}^{S} \mu_{js} = 1$. And $\sigma_s > 1$ represents the elasticity of substitution between industry s varieties. The second bracketed term represents the multiplicative damages from pollution. The aggregate stock of transboundary pollution emitted in all regions across all industries is $Z = \sum_{i=1}^{N} Z_i$ and η_j dictates the social cost of emissions.[6] The consumer's decision has two stages. In the first stage, preferences given in

[6] I assume that pollution is a pure externality coming from industrial activity and consumers ignore the last term in equation (3.1) when they make consumption decisions. The parameter η_j captures the regional social cost of carbon and dictates the marginal damages from pollution. The disutility from global emissions is the only feedback loop from environment to economy in this model, therefore changes in environmental quality do not affect productivity or factor endowments. Similar functional forms for climate damages

equation (3.1) imply that consumers in region j spend the share μ_{js} of income on industry s goods. In the second stage, consumers allocate their income across varieties in industry s. Therefore, consumers maximize utility subject to the budget constraint,[7]

$$\int_0^{M_{is}} p_{is}\theta_{ijs}\tau_{ijs}x_{ijs} = \mu_{js}X_j \tag{3.2}$$

where p_{is} is the factory price of an industry s variety from region i and $\theta_{ijs} \geq 1$ is the iceberg trade cost of shipping industry s varieties from region i to j, therefore $p_{is}\theta_{ijs}$ is the before tariff price of the industry s variety imported from region i to region j. Governments can impose tariffs on imports. t_{ijs} represents the industry-specific ad valorem tariff imposed by region j on imports from region i and $\tau_{ijs} = 1 + t_{ijs}$. Finally, X_j denotes the total expenditure in region j.

Subsequently, utility maximization subject to the budget constraint implies that firms in industry s of region i face the demand

$$x_{ijs} = \frac{(p_{is}\theta_{ijs}\tau_{ijs})^{-\sigma_s}}{P_{js}^{1-\sigma_s}}\mu_{js}X_j \tag{3.3}$$

where P_{js} is the consumer price index of industry s varieties in region j. Preferences imply that the consumer price index is given by $P_{js} = \left(\sum_{i=1}^{N} M_{is}(p_{is}\theta_{ijs}\tau_{ijs})^{1-\sigma_s}\right)^{\frac{1}{1-\sigma_s}}$.

Each variety ν_{is} is uniquely associated with an individual firm and in every region, production technology of industry s varieties is homogeneous across firms. Each region has a single productive factor which is inelastically supplied. The inverse production function of firms producing industry s varieties in region i is given by

are commonly used in environmental economics to determine the effects of emissions on climate and have recently been adopted by the international trade literature studying various environmental policy alternatives to quantify the impact of regulation on economic outcomes (Shapiro (2016), Larch and Wanner (2017), Kreickemeier and Richter (2018)).

[7] I omit the variety notation (ν_{is}) in the rest of the paper for simplicity.

$$l_{is} = \sum_{j=1}^{N} \frac{\theta_{ijs} x_{ijs}}{(1 - \xi_{is})\varphi_{is}} \quad (3.4)$$

where φ_{is} is the productivity level and l_{is} is the units of labour required at wage w_i to produce industry s varieties. Industrial activity creates pollution and government in region i imposes an environmental policy in the form of a carbon tax, e_i, per ton of pollution emitted on z_{is} tons of pollution emitted as a result of the production in industry s. In order to reduce emissions, firms divert a fraction ξ_{is} of the primary factor, labour, away from production and engage in abatement activities. Then, in region i, the fraction $(1 - \xi_{is})$ of this labour is used in production and the remaining ξ_{is} for pollution abatement in industry s.

Following Copeland and Taylor (2013), the production in industry s generates emissions according to the technology given by

$$z_{is} = (1 - \xi_{is})^{1/\alpha_{is}} \varphi_{is} l_{is} \quad (3.5)$$

where z_{is} is the tons of emissions from the production of industry s goods in region i and $\alpha_{is} \in (0, 1)$ represents the elasticity of pollution emissions intensity with respect to pollution abatement intensity.[8] From equation (3.5), pollution is a decreasing function of abatement and an increasing function of output. The level of abatement is determined in equilibrium and I assume that pollution regulations are stringent enough so that all firms engage in some level of abatement. As the government imposes a tax on emissions, e_i, firms engage in abatement activities. The increase in abatement increases firm profits by reducing the pollution tax payments but reduces profits as the share of productive resources allocated to

[8]Notice that using equations (3.4) and (3.5), ξ_{is} can be eliminated to obtain the joint production technology as $\sum_{j=1}^{N} \theta_{ijs} x_{ijs} = z_{is}^{\alpha_{is}} (\varphi_{is} l_{is})^{1-\alpha_{is}}$ where total industry s output in region i is written as a Cobb-Douglas production function of emissions and labour. Hence, pollution can equivalently be treated as another factor of production even though it is an outcome of the production process. As a result, α_{is} can also be described as pollution tax payments as a share of total production costs in this interpretation. For a detailed discussion of equivalent interpretations of this abatement technology see Copeland and Taylor (2013).

abatement increases.

Given the production technology and the structure of pollution emissions in equations (3.4) and (3.5), firms in region i maximize industry profits

$$\pi_{is} = M_{is}\Big(\sum_{j=1}^{N} p_{is}\theta_{ijs}x_{ijs} - w_i l_{is} - e_i z_{is}\Big) \tag{3.6}$$

Profit maximization implies that firms producing industry s varieties in region i set prices with a constant markup over marginal costs so that

$$p_{is} = \frac{\sigma_s}{\sigma_s - 1} \quad \frac{w_i^{(1-\alpha_{is})} \quad e_i^{\alpha_{is}}}{\alpha_{is}^{\alpha_{is}}(1-\alpha_{is})^{(1-\alpha_{is})}\varphi_{is}^{(1-\alpha_{is})}} \tag{3.7}$$

Substituting the expressions in (3.3), (3.4), (3.5) and (3.7) into equation (3.6), given carbon tariffs, the industry profits become

$$\pi_{is} = \frac{1}{\sigma_s}\sum_{j=1}^{N} M_{is}\tau_{ijs}^{-\sigma_s}\left(\frac{\sigma_s}{\sigma_s - 1} \quad \frac{w_i^{(1-\alpha_{is})} \quad e_i^{\alpha_{is}}}{\alpha_{is}^{\alpha_{is}}(1-\alpha_{is})^{(1-\alpha_{is})}} \frac{\theta_{ijs}}{\varphi_{is}^{(1-\alpha_{is})}P_{js}}\right)^{1-\sigma_s} \mu_{js}X_j \tag{3.8}$$

Given the level of import tariffs and equation (3.7), the equilibrium price index can be expressed as

$$P_{js} = \left[\sum_{i=1}^{N} M_{is}\left(\frac{\sigma_s}{\sigma_s - 1} \quad \frac{w_i^{(1-\alpha_{is})} \quad e_i^{\alpha_{is}}}{\alpha_{is}^{\alpha_{is}}(1-\alpha_{is})^{(1-\alpha_{is})}\varphi_{is}^{(1-\alpha_{is})}}\theta_{ijs}\tau_{ijs}\right)^{1-\sigma_s}\right]^{\frac{1}{1-\sigma_s}} \tag{3.9}$$

In equilibrium, labour supply equals labour demand, $L_i = \sum_{s=1}^{S} M_{is}l_{is}$. Using equations (3.3), (3.4), (3.5) and (3.7), the labour market clearing condition becomes

$$w_i L_i = \sum_{s=1}^{S} \pi_{is}(\sigma_s - 1)(1 - \alpha_{is}) \tag{3.10}$$

Given the cost of emissions, the level of pollution in region i is determined in equilibrium. Then, the global pollution stock is the sum of pollution emissions in all regions

$$Z = \sum_{i=1}^{N} Z_i \tag{3.11}$$

where the total cost of emissions in country i is given by

$$e_i Z_i = \sum_{s=1}^{S} \pi_{is}(\sigma_s - 1)\alpha_{is} \tag{3.12}$$

Finally, total expenditures in region j equals total income given by the sum total factor income, firm profits and lump-sum payments of tariff revenue:

$$\begin{aligned} X_j = {} & w_j L_j + e_j Z_j + \sum_{s=1}^{S} \pi_{js} \\ & + \sum_{i=1}^{N} \sum_{s=1}^{S} t_{ijs} M_{is} \tau_{ijs}^{-\sigma_s} \left(\frac{\sigma_s}{\sigma_s - 1} \frac{w_i^{(1-\alpha_{is})} e_i^{\alpha_{is}}}{\alpha_{is}^{\alpha_{is}} (1-\alpha_{is})^{(1-\alpha_{is})}} \frac{\theta_{ijs}}{\varphi_{is}^{(1-\alpha_{is})} P_{js}} \right)^{1-\sigma_s} \mu_{js} X_j \end{aligned} \tag{3.13}$$

where total tariff revenue is derived from $TR_j = \sum_{i=1}^{N} \sum_{s=1}^{S} t_{ijs} M_{is} x_{ijs} p_{is} \theta_{ijs}$ using the expressions on x_{ijs} and p_{is}.

The conditions given in equations (3.8), (3.9), (3.10), (3.11) and (3.13) define the equilibrium in this economy:

Definition 3.1. A general equilibrium in this economy is a system of equations (3.8), (3.9), (3.10), (3.11) and (3.13) which can be solved for wages $\{w_i\}_{i=1}^{N}$, aggregate stock of emissions $\{Z\}$, total expenditures $\{X_j\}_{j=1}^{N}$, prices $\{P_{js}\}_{j,s=1}^{N,S}$ and industry profits $\{\pi_{is}\}_{i,s=1}^{N,S}$ given the set of import tariffs $\{t_{ijs}\}_{i,j,s=1}^{N,S}$, cost of emissions $\{e_i\}_{i=1}^{N}$, and parameters $\{M_{is}, \theta_{ijs}, \varphi_{is}, \sigma_s, \alpha_{is}\}_{i,j,s=1}^{N,S}$.

The set of parameters $\{M_{is}, \theta_{ijs}, \varphi_{is}\}$ required to solve the equilibrium conditions are difficult to observe and measure. For example, barriers to trade captured by θ_{ijs} are rarely observed. Even when accurate data on freight expenditures are available in monetary terms, these may paint an incomplete picture of trade barriers since risk of damage in transit, communication-based barriers or time spent in transit can rarely be captured.[9] Data on

[9] See Anderson and Van Wincoop (2003), Evans and Harrigan (2005) and Hummels (2007).

these parameters are not necessary when the equilibrium conditions are expressed as relative changes from the baseline equilibrium. As commonly applied in the literature, following Dekle et al. (2008), rather than attempting to measure these parameters, I rewrite the equilibrium conditions in relative changes. This technique proceeds as follows. Let x denote the value of a variable in the model in the baseline equilibrium and x' denote its value in the counterfactual scenario, then $\hat{x} = x'/x$ is the relative change in x due to the counterfactual. Rewritten in changes, the equilibrium conditions given a change in the set of import tariffs become:

$$\hat{\pi}_{is} = \sum_{j=1}^{N} a_{ijs} \hat{\tau}_{ijs}^{-\sigma_s} \left(\frac{\hat{w}_i^{(1-\alpha_{is})}}{\hat{P}_{js}} \right)^{1-\sigma_s} \hat{X}_j \tag{3.14}$$

where $a_{ijs} = \frac{Tijs}{\sum_{n=1}^{N} T_{ins}}$ and $T_{ijs} = M_{is} \tau_{ijs}^{-\sigma_s} \left(\frac{\sigma_s}{\sigma_s - 1} \frac{w_i^{(1-\alpha_{is})} e_i^{\alpha_{is}}}{\alpha_{is}^{\alpha_{is}} (1-\alpha_{is})^{(1-\alpha_{is})}} \frac{\theta_{ijs}}{\varphi_{is}^{(1-\alpha_{is})} P_{js}} \right)^{1-\sigma_s} \mu_{js} X_j$ is the expression for bilateral trade flows between country j and i in industry s.

$$\hat{P}_{js} = \left[\sum_{i=1}^{N} \gamma_{ijs} \left(\hat{w}_i^{(1-\alpha_{is})} \hat{\tau}_{ijs} \right)^{1-\sigma_s} \right]^{\frac{1}{1-\sigma_s}} \tag{3.15}$$

where $\gamma_{ijs} = \frac{\tau_{ijs} Tijs}{\sum_{m=1}^{N} \tau_{ims} T_{ims}}$.

$$\hat{w}_i = \sum_{s=1}^{S} \delta_{is} \hat{\pi}_{is} \tag{3.16}$$

where $\delta_{is} = \frac{\sum_{j=1}^{N} \frac{(\sigma_s - 1)(1-\alpha_{is})}{\sigma_s} T_{ijs}}{\sum_{t=1}^{S} \sum_{n=1}^{N} \frac{(\sigma_t - 1)(1-\alpha_{it})}{\sigma_t} T_{int}}$.

$$\hat{Z}_i = \sum_{s=1}^{S} \zeta_{is} \hat{\pi}_{is} \tag{3.17}$$

where $\zeta_{is} = \frac{\sum_{j=1}^{N} \frac{(\sigma_s - 1)\alpha_{is}}{\sigma_s} T_{ijs}}{\sum_{t=1}^{S} \sum_{n=1}^{N} \frac{(\sigma_t - 1)\alpha_{it}}{\sigma_t} T_{int}}$ and the corresponding change in aggregate pollution stock is $\hat{Z} = \sum_{i=1}^{N} k_i \hat{Z}_i$ where $k_i = Z_i / \sum_{n=1}^{N} Z_n$.

$$\hat{X}_j = \frac{w_j L_j}{X_j}\hat{w}_i + \frac{e_j Z_j}{X_j}\hat{z}_j + \sum_{s=1}^{S}\frac{\pi_{js}}{X_j}\hat{\pi}_{js} + \sum_{i=1}^{N}\sum_{s=1}^{S}\frac{t'_{ijs}T_{ijs}}{X_j}\hat{\tau}_{ijs}^{-\sigma_s}\left(\frac{\hat{w}_i^{(1-\alpha_{is})}}{\hat{P}_{js}}\right)^{1-\sigma_s}\hat{X}_j \tag{3.18}$$

Given the changes in import tariffs, equations (3.14), (3.15), (3.16), (3.17), and (3.18) can be solved to obtain $\hat{w}_i$, $\hat{Z}_i$, $\hat{\pi}_{is}$, $\hat{X}_j$, and $\hat{P}_{js}$ for all $i,j \in N$ and $s \in S$. Notice that from equations (3.8), (3.10), (3.12) and (3.13), the total industry-level profits, labour income, pollution tax revenues and trade balance condition across regions can be written in terms of parameters α_{is}, σ_s, import tariffs, τ_{ijs}, and bilateral trade flows, T_{ijs}, such that $\pi_{is} = \frac{1}{\sigma_s}\sum_{j=1}^{N} T_{ijs}$, $w_i L_i = \sum_{j=1}^{N}\sum_{s=1}^{S}\frac{(\sigma_s-1)(1-\alpha_{is})}{\sigma_s}T_{ijs}$, $e_i Z_i = \sum_{j=1}^{N}\sum_{s=1}^{S}\frac{(\sigma_s-1)\alpha_{is}}{\sigma_s}T_{ijs}$, and $X_j = \sum_{i=1}^{N}\sum_{s=1}^{S}\tau_{ijs}T_{ijs}$.

Welfare effects of a counterfactual policy that changes total emissions can easily be observed from the model. By substituting utility maximizing levels of x_{ijs} for a given price index and income into the utility function, the indirect utility function in region j is obtained as

$$\bar{U}_j = \frac{X_j}{P_j}\left[\frac{1}{1+\left(\eta_j^{-1}\sum_{i=1}^{N} Z_i\right)^2}\right] \tag{3.19}$$

In equation (3.19), welfare in region j is defined as the product of real income and the damages from pollution. The relative change in welfare can then be calculated from

$$\hat{W}_j = \frac{\hat{X}_j}{\hat{P}_j}\left[\frac{1+\left(\eta_j^{-1}\sum_{i=1}^{N} Z_i\right)^2}{1+\left(\eta_j^{-1}\sum_{i=1}^{N} Z'_i\right)^2}\right] \tag{3.20}$$

where $\hat{P}_j = \prod_{s=1}^{S}(\hat{P}_{js})^{\mu_{js}}$ and $\sum_{i=1}^{N} Z'_i$ is the total emissions in the counterfactual equilibrium.

The equilibrium described in equations (3.14), (3.15), (3.16), (3.17), and (3.18) is based on a balanced trade assumption. Therefore, $NX_i = \sum_{j=1}^{N}\sum_{s=1}^{S}(T_{ijs} - T_{jis}) = 0$ must hold. This condition is violated in the data. I adopt the approach suggested in Dekle et al. (2008) and

Ossa (2014) and first purge the raw data from aggregate trade imbalances, then conduct the analyses using the purged dataset. Particularly, I solve a modified system of equations where equation (3.18) is augmented to include an additional term that captures trade imbalances, $\frac{NX_j \widehat{NX}_j}{X_j}$, where $NX_j = \sum_i^N \sum_s^S (T_{ijs} - T_{jis})$ represents the set of trade deficits taken from data. Solving this modified system of equations that define the equilibrium by keeping tariff changes equal to one, such that $\hat{\tau}_{ijs} = 1$ and setting $NX_j' = 0$ delivers a trade matrix without trade imbalances that I use to conduct the analyses presented in section 3.4. Table C.1 summarizes the effects of this procedure on raw trade data.

3.3 From Theory to Data

Solving the model in relative changes as presented in section 3.2 minimizes the data requirements. To calibrate the model and perform the scenarios described in section 3.4, I need data on bilateral trade flows, existing bilateral tariffs, production and carbon emissions, all at the country and industry-level. I aggregate the data into 5 regions and 15 tradable industries. Table C.5 provides a list of industries included in the analysis. To represent the world economy, I include Canada, China, 28 countries in the European Union aggregated as a regional entity, the United States and a constructed rest of the world (RoW). The choice of regions is motivated by the focus of this paper. China, the European Union and the United States are important parties to current and previous climate agreements with their high emissions and international trade exposures. Canada is an important trade partner of the United States and a strategic player in the case of a mutual tariff war. Regional entities are treated as sovereign individual countries. I describe the data in further detail and the construction of key parameters in the rest of this section.

3.3.1 Trade and Production Data

Data on bilateral trade flows in 2011 are from the United Nations Statistical Division (UNSD) Commodity Trade (COMTRADE) database. The original data is reported in the 2007 Harmonized System classification system, using the concordance tables from the World Bank's World Integrated Trade Solution (WITS) server, I compute the value of trade flows according to the ISIC Rev. 3 industry classification adopted in this paper. I obtain industry-level gross output and value-added data for all countries from the World Input Output Database (WIOD). Output and trade data are then used to calculate intra-national trade (production made and sold within each country). All data are expressed in nominal US dollars and no conversion is necessary. Table 3.1 breaks down the average export shares across regions. The US is the primary destination of exports from Canada. Apart from the RoW, the EU and the US are important trade partners for China with export shares amounting to about 25 and 18 percent respectively. The US delivers most of its exports to the RoW while exports to the EU and Canada follows with 20 and 13 percent respectively. Large exports of Canada and China to the US imply high vulnerabilities of these countries for the case of a possible retaliation from US.

Table 3.1: Average Export Shares (in %)

	Canada	China	EU	US
Canada	-	6.30	8.70	63.28
China	2.36	-	24.55	17.91
EU	0.79	3.67	-	4.70
US	13.45	8.35	20.17	-

Note: Displays the export shares in percentages in the baseline equilibrium from row region to column region.

3.3.2 Carbon Emissions

The industry-level emissions cost share of firms in region i, α_{is}, cannot be directly calculated since climate policy stringency is not observable in the data. However, it can be inferred from the data on energy consumption assuming a perfectly linear relationship between energy consumption and emissions. Let $e_i = \frac{ec_i}{z_i}$ denote the average implicit cost of emissions in region i where ec_i is the total cost of energy and z_i is total emissions in region i. The WIOD's Energy Use dataset provides detailed data on emission-relevant energy use from different fuels at the industry-level for 40 countries plus the RoW.[10] These are given in terajoules. Using annual prices reported in the International Energy Agency (IEA) Energy Prices and Taxes and the conversion factors adopted by the IEA, I calculate energy expenses in each industry for all regions.[11] Industry emissions for each region are calculated from the WIOD Environmental Accounts. Using these data, I construct a region's average implicit cost of emissions as the sum of expenditures on energy sources divided by total emissions.[12] I obtain the corresponding emission cost shares, α_{is}, for each industry in region i by using information on industry emissions and the previously calculated implicit cost of emissions.

Combining the data explained in section 3.3.1 with the CO_2 emissions data, Table 3.2 highlights relative importance and vulnerabilities of each region for carbon tariffs. Apart from the constructed RoW, the US is the largest economy and the second largest emitter after China. China, Europe and the US account for about 50 percent of the world GDP and 52 percent of global CO_2 emissions. With its large emissions and high export shares, China is the most vulnerable region in the case of a tariff war.

[10]This dataset excludes the non-energy use of fuels so provides a direct link between energy use and energy related emissions.

[11]The WIOD uses the IEA data on fuel prices to convert monetary entries on energy use in the input-output tables to physical quantities. I use the energy prices provided by the IEA to be consistent with the WIOD. For more information on the construction of the WIOD Environmental Accounts, see Genty et al. (2012).

[12]This is the average cost of emissions for the industry. Households' energy expenditures and corresponding consumption emissions are not included in the analyses.

Table 3.2: Shares of GDP, Exports and CO_2 Emissions, (in %)

	GDP Share	Export Share	CO_2 Share
Canada	2.43	36.63	1.85
China	10.33	23.70	27.54
EU	18.58	48.86	10.06
US	21.17	17.72	14.59
RoW	47.49	31.69	45.96

Note: The first column displays each region's share in global GDP. The second column displays exports as a share of regional GDP. The last column displays the share of each region in global emissions. All values are in percentages. First and last columns sum up to 100 percent.

3.3.3 Trade Elasticities

I estimate trade elasticities using the methodology suggested by Caliendo and Parro (2015). It can be directly applied to the model presented in section 3.2. Defining the value of trade flows in industry j between region i and j as $X_{ijs} = M_{is}p_{is}\theta_{ijs}x_{ijs}$ and using equations (3.3) and (3.7) imply

$$X_{ijs} = M_{is}\tau_{ijs}^{-\sigma_s}\left(\frac{\sigma_s}{\sigma_s - 1}\frac{w_i^{(1-\alpha_{is})} \quad e_i^{\alpha_{is}}}{\alpha_{is}^{\alpha_{is}}(1-\alpha_{is})^{(1-\alpha_{is})}\varphi_{is}^{(1-\alpha_{is})}}\right)^{1-\sigma_s}\theta_{ijs}^{1-\sigma_s}P_{js}^{\sigma_s-1}\mu_{js}X_j \tag{3.21}$$

Consider trade flows in industry s between three countries indexed by i, n, and k. Cross-product of the value of trade between these three countries is $X_{inj}X_{nhj}X_{hij}$. Dividing this cross-product by the same term with the trade flows in the opposite direction and substituting equation (3.21) yields

$$\frac{X_{inj}X_{nhj}X_{hij}}{X_{nij}X_{hnj}X_{ihj}} = \left(\frac{\tau_{inj}\tau_{nhj}\tau_{hij}}{\tau_{nij}\tau_{hnj}\tau_{ihj}}\right)^{-\sigma_s}\left(\frac{\theta_{inj}\theta_{nhj}\theta_{hij}}{\theta_{nij}\theta_{hnj}\theta_{ihj}}\right)^{1-\sigma_s} \tag{3.22}$$

In equation (3.22), all terms specific to a particular country cancel out and only the ones specific to country pairs remain. The trade costs are generally assumed to be composed of four parts, a pair-specific, a destination-specific and an origin-specific component, and a stochastic part, namely $\theta_{inj} = \iota_{inj}\iota_n\iota_i\epsilon_{inj}$. Assuming bilateral trade costs, are symmetric so that $\iota_{inj} = \iota_{nij}$, equation (3.22) simplifies to

$$\frac{X_{inj}X_{nhj}X_{hij}}{X_{nij}X_{hnj}X_{ihj}} = \left(\frac{\tau_{inj}\tau_{nhj}\tau_{hij}}{\tau_{nij}\tau_{hnj}\tau_{ihj}}\right)^{-\sigma_s} \left(\frac{\iota_{inj}\iota_{nhj}\iota_{hij}}{\iota_{nij}\iota_{hnj}\iota_{ihj}}\right)^{1-\sigma_s} \quad (3.23)$$

Finally, taking logs and defining the random disturbance term as $\epsilon_{inj} \equiv \frac{\iota_{inj}\iota_{nhj}\iota_{hij}}{\iota_{nij}\iota_{hnj}\iota_{ihj}}$ yields the estimating equation in Caliendo and Parro (2015)

$$\ln\left(\frac{X_{inj}X_{nhj}X_{hij}}{X_{nij}X_{hnj}X_{ihj}}\right) = -\sigma_s \ln\left(\frac{\tau_{inj}\tau_{nhj}\tau_{hij}}{\tau_{nij}\tau_{hnj}\tau_{ihj}}\right) + \epsilon_{inj} \quad (3.24)$$

The main identifying assumption for equation (3.24) to yield consistent estimates is that pair-specific tariffs are independent of non-tariff barriers to trade. I estimate this equation for 15 industries using tariff and trade data for a pool of 37 countries. The resulting estimates are displayed in Table 3.3.

Table 3.3: Trade Elasticities

Industry		
Agriculture	5.43†††	(1.19)
Mining	20.06†††	(4.81)
Food Products	5.06†††	(0.61)
Textile	5.84†	(0.68)
Wood Products	34.17†††	(3.25)
Paper and Printing	4.12†	(3.00)
Petroleum	14.68†††	(6.92)
Chemicals	9.11†††	(1.53)
Plastic Products	27.29†††	(3.31)
Mineral Products	14.77†††	(1.59)
Metals	11.53†††	(1.25)
Machinery and Equipment	5.02††	(2.10)
Electrical and Optical	15.67†††	(0.96)
Transport	8.09†††	(0.73)
Other	7.93†††	(1.35)

Note: Displays the results of the estimating equation (3.24). The average trade elasticity for all industries is 15.45 with $p < 0.000$ and $se = 1.75$. Standard errors in parenthesis. $\dagger\dagger\dagger$ $p < 0.01$, $\dagger\dagger$ $p < 0.05$, $\dagger$ $p < 0.1$.

3.3.4 Climate Damages

Estimation of the social cost of carbon emissions (SCC) is beyond the scope of this paper. Therefore, I rely on values from multiple sources to determine the parameter, η_j, that governs the regional damages from aggregate emissions. SCC is the the present value of future damages as a result of a ton of increase in emissions in a particular year. It can be calculated at the global scale or for different regions. There is a large variation in the estimates of SCC in the literature due to the uncertainty involved in the sensitivity of the climate to changes in carbon dioxide concentrations, the monetization of damages from these changes and assumed level of risk aversion.[13] I solve for the values of η_j using various estimates of SCC in the literature. Specifically, I differentiate the welfare equation (3.19) with respect to total emissions, $\sum_{i=1}^{N} z_i$, and this equals the SCC in region j from a marginal increase in global emissions:

$$\frac{\partial\left(\frac{X_j}{P_j}\left[\frac{1}{1+\left(\eta_j^{-1}\sum_{i=1}^{N} z_i\right)^2}\right]\right)}{\partial\left(\sum_{i=1}^{N} z_i\right)} = scc_j \tag{3.25}$$

Then, I calculate the derivative and rewrite scc_j as region j's share of global SCC

$$-\frac{X_j}{P_j}\frac{2\eta_j^{-2}\sum_{i=1}^{N} z_i}{\left[1+\left(\eta_j^{-1}\sum_{i=1}^{N} z_i\right)^2\right]^2} = scc_w\frac{sc_jX_j/P_j}{\sum_{i=1}^{N} sc_iX_i/P_i} \tag{3.26}$$

where sc_j is the share of damage in the GDP of region j due to the warming in climate. From equation (3.26), η_j can be calculated using data from various sources.

Interagency Working Group on the Social Cost of Carbon (2016) provides estimates of global SCC (scc_w) ranging from \$10 to \$212 under different parameter assumptions. I calculate the values of η_j based on the assumption that a ton increase in emissions decreases

[13] For detailed discussions on the calculation of SCC under different assumptions, see Newbold et al. (2010) and Arrow et al. (2014).

global GDP by $42. This is the estimate of Interagency Working Group on the Social Cost of Carbon (2016) assuming a 3 percent discount rate for the year 2020 and is also consistent with values adopted by other governments and in the range of results estimated under alternative approaches.[14] Nordhaus and Boyer (2000) calculate impacts in 13 regions of a 2.5°C warming in climate measured as percent of GDPs. I rely on their calculations to calculate the share of global costs each region has to bear (sc_j). Nordhaus and Boyer (2000) calculate the percentage of loss in GDP as 0.45% for the US, 0.22% for China, and 2.83% for Europe. Canada is projected to benefit from climate change but the model presented in here does not allow for benefits. Therefore, I assume that Canada faces zero damage to its GDP from climate change. I assume the global average (1.50%) for the ROW. Real GDP values are calculated from the Penn World Table (version 9.0).[15]

3.4 Results

In this section, I first present the environmental and economic consequences of the emission reduction pledges in the Paris Agreement. This forms the benchmark scenario where all regions participate. Then, I present the effects of the US withdrawal from the Paris Agreement under two scenarios. First, when the US withdraws, other regions achieve their initial emission reduction targets and as a second scenario, the committing regions choose to compensate for the effect of the US withdrawal on global emissions and increase their efforts to reach the initial emission reduction level in the benchmark scenario. Then, before proceeding with the calculation of optimal carbon tariffs, in order to compare results from this framework to the results of the studies in the current literature, I turn to calculating carbon tariffs using an approach commonly adopted in the literature. Specifically, I calculate

[14]The Canadian SCC estimate discounted at 3 percent is $40.7 for 2020 (Environment and Climate Change Canada, 2016). See also Ricke et al. (2018).

[15]I use expenditure-side real GDP at current PPPs (in mil. $2011 US - \$$) converted to 2009 values from price levels of household consumption. Aggregate prices for EUR and ROW are calculated as weighted averages using expenditures as weights. Data is available at https://www.rug.nl/ggdc/productivity/pwt/.

the exogenous carbon tariffs as the gap between implicit costs of emissions between regions proportional to the emission intensity of production in the importing region. Again, the effects of these carbon tariffs are evaluated under two scenarios. First, I study the scenario under which committed regions to the Paris Agreement impose carbon tariffs on imports from the US. However, there are large differences across regions in terms of implicit costs of emissions. Paris Agreement pledges are determined unilaterally in each country in a non-cooperative manner and regions like the EU and Canada which already have high implicit emission costs commit to reducing their emissions more than other regions with low implicit costs of emissions. This is a reason for reactions against environmental policies in developed countries. Therefore, regions with high emission costs may decide to impose carbon tariffs on imports from low emission cost regions regardless of the status in the Paris Agreement. In this second scenario, I show the effects when all regions including the US consider imposing carbon tariffs. Then, I calculate optimal unilateral carbon tariffs at the industry-level imposed by committing regions on imports from the US. These are the tariffs imposed by regions in a non-cooperative manner without the fear of retaliation from the US. The effects of a possible retaliation from the US in the form of import tariffs are presented in the following section. Finally, I show the effects of a worldwide tariff war where committing regions respond to the retaliation from the US by changing their import tariffs.

3.4.1 Effects of the NDCs in the Paris Agreement

Parties to the UNFCCC agreed at the 20th session of the Conference of the Parties (COP20) in December 2014 to set out their "intended nationally determined contributions" (INDCs). When countries formally ratify the Paris Agreement, their INDCs become "nationally determined contributions" (NDCs). I use these national emission reduction pledges published by the UN and calculate the required emission reduction levels in the model base year 2011 using the historical emissions data collected in the UNFCCC National Inventory Submissions.[16]

[16] National pledges are available in the NDC Registry held by the UNFCCC, see https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx.

(I)NDCs differ in terms of target years, therefore, a standardization is necessary to make targets comparable. For example, while the US pledges to reduce emissions by 26-28% from 2005 reference levels until the target year 2025, the target year for the EU is 2030. Due to substantial uncertainties involved in GDP projections, I abstain from standardizing emission reduction targets from a business as usual (BAU) scenario in the future. Instead, assuming the data in 2011 as the BAU case, I transform the (I)NDCs into emission reduction targets from 2011 levels using historical data. I use the lower bound of the target when a range of targets are provided in the (I)NDCs. China pledges to reduce its emission intensity by 60-65% below 2005 levels in 2030 and this requires no reduction from the BAU level in 2011. However, I include a mild target of 3% reduction from the BAU path for China to reflect its increasing involvement in climate negotiations. The heterogeneity across countries in terms of emission reduction targets is evident in Figure 3.1. While most developing countries in Asia and Africa have very small targets or just commit not to increase their emissions, more developed countries and large parts of South America commit to lower their emissions by more than 20 percent. In this section, I analyse the economic effects of a scenario in which all regions with (I)NDCs reach their targets and the constructed RoW keeps its emissions constant.[17]

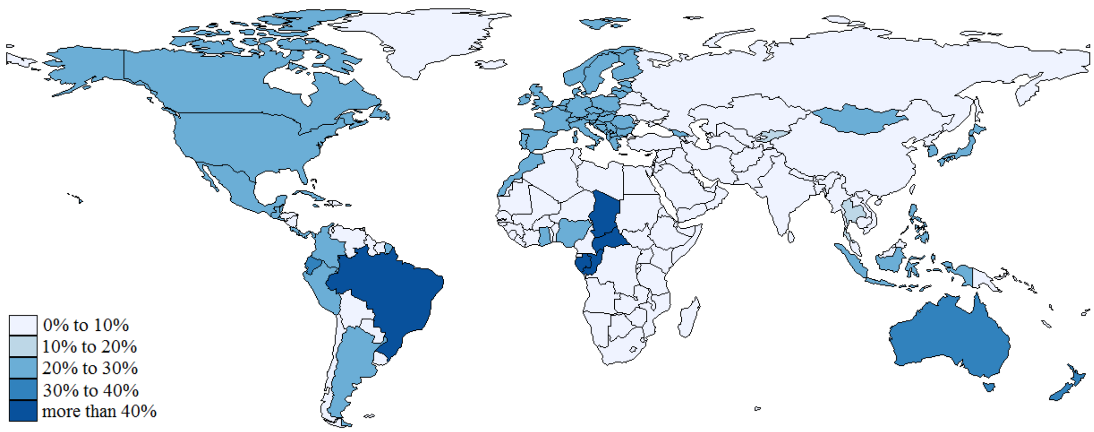
Employing the model presented in section 3.2, I quantify the effects of complying with the effective emission reduction targets in each region.[18] Imposing the emission changes in

Historical emissions are available in National Inventory Reports at https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2018.

[17]160 (I)NDCs submitted by 2016 cover emissions from 187 parties to the UNFCCC which were responsible for about 96% of world emissions in 2012. Determining what the (I)NDCs will deliver in terms of emission reductions is not straightforward since many countries provide a range of pledges covering different parts of the economy, and for a number of countries (like Russia) the targets suggest emission levels above their no-policy baseline scenarios. This is why I assume that the constructed RoW at least keeps its emissions constant in the counterfactual scenario in which all other regions meet their targets. For more information on how countries compare in their (I)NDCs, see Rogelj et al. (2016).

[18]I assume that each region satisfies the emission reduction pledges by reducing emissions in the industries included in this analysis at the same percentage as described in the NDCs. For example, the effective reduction target of the US is 20% from the BAU levels, I assume that emissions from the tradable industries are reduced by the same percentage. Countries in reality, can satisfy their pledges by targeting certain

Figure 3.1: Emission Reduction Targets in the Paris Agreement



Note: Displays the emission reduction targets specified in the (intended) NDCs calculated as reductions below the model base year 2011. The average target is shown for the EU countries.

the model delivers a set of changes in the cost of emissions.[19] Results are presented in Table 3.4.

Table 3.4: Effects of Achieving the Paris Agreement Targets across Regions

Region	△Cost of Emissions	△Emissions	△Real Income	△Exports
Canada	$95.4	-26.6	-0.95	-0.69
China	$7.2	-3.0	-0.11	0.14
EU	$185.1	-27.0	-1.41	-1.02
RoW	$2.3	0.0	0.03	0.30
USA	$64.0	-20.0	-0.76	-0.33

Note: Displays the effects of meeting the targets as agreed in the Paris Agreement. Changes in the cost of emissions are in dollars. Changes in emissions, real income and exports are in percentages.

The first column shows the increase in the implicit cost of emitting an extra unit of CO_2 when regions commit to meeting their Paris Agreement targets.[20] Differences across regions

industry and consumption emissions.

[19]Emission reduction targets can be achieved through different policy instruments like carbon pricing, emission intensity standards, and subsidies on clean technologies. For simplicity, I calculate the total cost of achieving the required reduction rate in each region and assume that the additional cost is imposed on production as a tax on emissions.

[20]Notice that relatively less emission intensive non-tradable industries such as various services industries

reflect both the effective emission reduction targets and the ease of substituting away from carbon intensive goods in consumption and production decisions. High costs in Canada and the EU are related to their relatively ambitious reduction pledges. The second column shows the change in total emissions. Global emissions decrease by 6 percent. In terms of welfare, Canada bears the largest cost of global emission reduction since there are zero benefits to its GDP from a decrease in global emissions. Other regions experience increases in welfare as global emissions decrease. However, measuring the change in welfare this way masks the impact on real income, i.e. the change in welfare net of environmental effects. The isolated change in real income is presented on the third column. The difference between the change in welfare and real income depends on the size of the global emission reduction and the magnitude of the regional social cost of carbon. All regions lose except the RoW. The RoW with no reduction target experiences a welfare increase from the decrease in global emissions as other regions commit to their pledges and also from the increased comparative advantage in the production of emission intensive goods. Europe experiences the biggest difference between two welfare measures since it enjoys the largest benefit from avoided emissions as explained in section 3.3.4. The last column shows the changes in total exports. Looking into the change in trade in more detail reveals the effect of some regional features. Canada's total exports decline by 0.69 percent. The primary destination for Canada's relatively emission intensive chemicals industry is the US. While Canada's exports decline in many industries, its chemicals exports increase. This is mainly due to the decrease in production in the US. Even though the increase in the cost of emissions is larger in Canada than in the US, Canada's emission intensity in chemicals production is small compared to other countries. On the other hand, the biggest losers in Canada in terms of production and exports are the mining and petroleum industries. The primary destination for exports in these industries is again the US. However, as the prices increase in Canada, the US increases production and its

are not included in the analysis and Paris Agreement pledges are achieved through reductions in emissions from the production of 15 industries included in this paper. Since introduction of non-tradable industries may change the level of increase in the cost of emissions, these values presented here are informative when compared across regions.

imports from the RoW. China's mining industry is very emission intensive, but its exports to all other regions increase in the counterfactual equilibrium due to the small change in its cost of emissions compared to its competitors in developed regions. Exports of petroleum products of the RoW increase and this is the main source of increase in the total exports of the RoW.

3.4.2 Effects of US Withdrawal

A natural question that follows the results of the previous section is the consequences of a possible US withdrawal. In 2017, it was officially announced that the United States will stall all contributions to the United Nations' Green Climate Fund and withdraw from the Paris Agreement. Given that the US is the world's second largest emitter and the largest economy, a possible withdrawal will potentially have consequences for the compliance prospects of the Paris Agreement. In this section, I quantify the effects of a US withdrawal when other regions fulfill their emission reduction requirements by imposing a tax on domestic emissions. I assume that no sanctions are imposed on the US by its trading partners.

Table 3.5 reports changes in the cost of emissions, regional emissions, real income and total exports. The US defects from the Paris Agreement and does not undertake any policies to control its emissions, therefore the change in its cost of emissions is zero. The committed regions then adjust the levels of carbon taxes so that they still achieve the same emission reduction targets. This results in an about 2 percent increase in emissions from the production in the US. Exports of all committed regions are lower because the US is able to provide imports at a lower cost. The increases in average regional price indices are lower compared to the results of the benchmark scenario. Welfare increases in all regions are also lower compared to the benchmark since the achieved global emission reduction is lower. Even though nominal income levels in committed regions are lower than the benchmark scenario, smaller increases in average prices result in higher real incomes in some regions compared to the benchmark scenario.

Table 3.5: Effects of the US Withdrawal

Region	△Cost of Emissions	△Emissions	△Real Income	△Exports
Canada	$94.5	-26.6	-0.95	-0.81
China	$6.8	-3.0	-0.10	0.09
EU	$183.5	-27.0	-1.42	-1.10
RoW	$1.9	0.0	0.03	0.25
USA	$0	2.1	0.01	0.23

Note: Displays the effects of a possible US withdrawal from the Paris Agreement. Changes in the cost of emissions are in dollars. Changes in emissions, real income and exports are in percentages.

Instead of aiming for satisfying their initial pledges, the committed regions may step up to make up for the US withdrawal with compensating emission reductions. This way, the global emission reductions can be kept equal to the level consistent with the implementation of NDCs by all parties. The results of this scenario is presented in Table 3.6.

Results show that proportional decreases in emissions are larger than the ones under the benchmark scenario. When committing regions further limit their emissions to achieve the global emission reduction target of the Paris Agreement, US welfare increases more due to improved competitiveness in export markets. The largest increases in exports of the US involve the products imported by the EU. On average, US exports of mining, minerals and chemicals products experience the largest increase. Due to its small contribution to the decrease in global emissions, the RoW still experiences a mild increase in welfare and exports.

Table 3.6: Effects of the US Withdrawal (with constant global emissions)

Region	△Cost of Emissions	△Emissions	△Real Income	△Exports
Canada	$97.6	-29.7	-1.24	-1.16
China	$7.4	-5.0	-0.18	-0.00
EU	$186.0	-28.8	-1.61	-1.39
RoW	$2.3	-2.1	0.02	0.17
USA	$0	2.2	0.05	0.32

Note: Displays the effects of a possible US withdrawal from the Paris Agreement conditional on equal decrease in global emissions with the benchmark scenario. Changes in the cost of emissions are in dollars. Changes in emissions, real income and exports are in percentages.

3.4.3 Carbon Tariffs

When the US defects from the Paris Agreement, the remaining regions can either comply with their initial targets but suffer the negative environmental consequences of the US withdrawal or reduce their production emissions more than their initial targets to preserve the global objective of the Paris Agreement and suffer the economic consequences. Both cases create incentive for the US to increase its production and emission levels. To attenuate the emission increase from additional US production, compliant regions may choose to impose carbon tariffs on US imports. Before investigating the consequences of strategic interactions in environmental policy, I first evaluate the effects of exogenous carbon tariffs imposed on US imports. As explained by Böhringer et al. (2012), carbon tariffs are varied along three dimensions: embodied emission coverage, industry coverage and tariff rate differentiation. In this paper, I quantify the economic and environmental consequences of carbon tariffs at the region and industry-level imposed on direct emissions from imports of all industries. The General Agreement on Tariffs and Trade (GATT) rules require that imports from all parties of the WTO be treated similarly, this implies that imports can be taxed only at a level equal to the gap between policy restrictiveness of two countries. Therefore, I calculate exogenous carbon tariffs as follows:

$$\tau^c_{ijs} = \begin{cases} 1 + \epsilon_{js}(e_j - e_i) & \text{if } e_j > e_i. \\ 1 & \text{otherwise.} \end{cases} \tag{3.27}$$

where ϵ_{js} is the emission intensity of production, e_j is the implicit cost of emissions in the importing region, and e_i is the implicit cost of emissions in the exporting region. Therefore, the larger the difference between two regions' costs of emissions, the higher is the tariff imposed by the importing region. The gap between the restrictiveness of environmental policy is multiplied by the emission intensity of production of industry s in the importer, this means that the emissions embodied in trade flows are calculated based on the emission intensity of the importing region. This is a product-based calculation of carbon tariffs. Since the resulting tariffs do not discriminate between regions based on the production technology abroad, calculating carbon tariffs this way is considered compatible with the WTO law (Böhringer et al., 2012). The resulting tariffs vary across industries and regions. Assessing the average industry tariffs weighted by trade flows yields that the highest average carbon tariff on imports to Canada is in petroleum products with 0.44 percent and on imports to the EU in chemicals with 0.28 percent. The RoW also imposes carbon tariffs on US imports, the highest of which is on petroleum products with 0.31 percent. Table C.3 shows the average trade-weighted tariffs at the industry-level on imports from the US. I apply these carbon tariffs calculated from equation (3.27) on US imports and the revenue from tariffs are recycled lump-sum to consumers in imposing regions. The costs of emissions are held constant.

Table 3.7 presents the effects of these carbon tariffs across regions. Comparing with the increase in emissions from the US withdrawal, carbon tariffs are quite effective in attenuating the increase. As a result of the tariffs, US emissions decrease by 1.9 percent. Tariffs also have minor implications for the real incomes of the committing regions. Implicit cost of emissions is lower in China than the US, hence there is no carbon tariff imposed by China in

Table 3.7: Effects of Carbon Tariffs on US Imports

Region	△Emissions	△Real Income	△Exports
Canada	0.1	0.04	0.02
China	0.1	0.01	0.03
EU	0.7	0.04	0.15
RoW	0.7	0.06	0.14
USA	-1.9	-0.30	-0.52

Note: Holding the cost of emissions constant in all regions, the table displays the effects of carbon tariffs imposed on US imports. Changes in emissions, real income and exports are in percentages.

the counterfactual equilibrium, the small change in China's exports is due to the increased competitiveness in the export markets when the US imports are sanctioned. The highest tariffs are imposed by the EU on imports of emission intensive industries like petroleum, chemicals, minerals and plastics. Canada in return increases its exports to the EU in these industries.

Even though the previous analysis establishes that the carbon tariffs imposed on the US imports partly alleviate the negative environmental effects of the US withdrawal, levelling off the carbon playing field on international markets requires equalizing differences in the levels of implicit costs of emissions across regions. In this hypothetical scenario, for each pair of regions, the region with the higher implicit cost of emissions imposes carbon tariffs on imports to eliminate the competitive advantage of the other region. Since carbon tariffs are calculated at the industry-level, for a given pair of regions, the resulting tariffs will be higher in industries with higher emissions intensities. Therefore, carbon tariffs in a global scenario function as carbon equivalent taxes between regions with differences in implicit costs of emissions. Table C.4 shows the resulting average trade-weighted carbon tariffs imposed by each region. Since China has the lowest implicit cost of emissions, imports to China are not subject to carbon tariffs. The restrictiveness of environmental policy implied by the implicit cost of emissions is on average higher in the RoW than China. The main reason for the average non-zero carbon tariffs in the RoW is this policy gap between China and the RoW. The EU has the highest implicit cost of emissions, therefore, while the EU imposes tariffs on imports from all regions, China has to pay tariffs. Canada and the US pay tariffs when exporting to the EU and impose carbon tariffs in most of the other cases. Carbon tariffs imposed on imports into the EU are the highest. Among all regions, the highest carbon tariffs are imposed on imports of emission intensive industries like mining, petroleum products, minerals, metals, and chemicals. Table 3.8 presents the effects of these carbon tariffs across regions. The aggregate changes in total emissions show that regions with relatively stricter environmental policies experience an increase in emissions while regions with low costs of emissions reduce their total emissions. The corresponding effect of carbon tariffs is a decrease in global emissions. Therefore, if carbon taxes relocate emissions from regions with strict environmental regulations to low carbon tax regions, carbon tariffs are successful in reversing this relocation. Welfare effects and the changes in real income are similar since the reduction in global emissions is small. The changes in real income are small but positive for regions that on average impose relatively larger carbon tariffs on their trading partners. While the increase in real income is 0.01 percent in Canada, the EU experiences a 0.7 percent increase in real income. China and the US lose about 2 percent of their real income.

3.4.4 Optimal Carbon Tariffs

As presented in the previous section, the purpose of "standard" carbon tariffs is to assure that exporting regions pay the same price on emissions embodied in trade as in the importing regions. However, these "standard" carbon tariffs are not determined by a social planner that seeks to maximize welfare in a region. Emissions arising from the production process affect regions from two channels. First of all, emissions from production are trans-boundary,

Table 3.8: Effects of Global Carbon Tariffs

Region	△Emissions	△Real Income	△Exports
Canada	0.3	0.01	0.02
China	-1.9	-0.18	-0.54
EU	1.1	0.66	1.23
RoW	0.9	0.20	0.08
USA	-0.9	-0.16	-0.44

Note: Holding the cost of emissions constant in all regions, the table displays the effects of carbon tariffs adopted by all regions. Changes in emissions, real income and exports are in percentages.

they accumulate in the atmosphere and reduce social welfare. This creates an environmental incentive for governments when choosing optimal carbon tariffs. Emissions also affect the production possibilities of regions. Governments can also set carbon tariffs in order to influence the terms of trade in their favour. This creates an economic incentive. Considering these channels and the differences in trade elasticities, there can be incentives for the importing regions to deviate from the rates of "standard" carbon tariffs. In this section, to compare the impact of these incentives on economic and environmental outcomes, I present the optimal carbon tariffs imposed by each region on imports from the US. In this scenario, I calculate the unilaterally optimal carbon tariffs for Canada, China, the EU and the RoW on the carbon content of imports from the US. These are calculated in a non-cooperative setting. As in previous scenarios, there are pre-existing import tariffs. Each importing region optimally decides on the industry-level carbon tariffs on embodied emissions in imports from the US calculated at the initial emission intensity of production in the importing region. The revenues are rebated in a lump-sum fashion to the consumers in the tariff imposing region. Table 3.9 presents the results.

The results show that committing regions have a large incentive to impose higher carbon

Table 3.9: Effects of Optimal Carbon Tariffs

Region	△Emissions	△Exports	△Real Income	
			Own	US
Canada	1.2	0.7	0.6	-0.1
China	1.0	1.6	0.8	-0.2
EU	1.1	3.2	1.2	-0.4
RoW	1.6	2.4	1.3	-0.3

Note: Displays the effects of optimal carbon tariffs adopted by all committing regions on imports from the US. Changes in emissions, real income and exports are in percentages. The column "own" shows the change in real income in each region, the column "US" shows the effect of the optimal carbon tariffs imposed by each row region on the real income of the US.

tariffs on the US imports compared to the tariffs in the previous section. All countries are motivated by the environmental and economic objectives to impose higher tariffs. This is why contrary to the analysis in the previous section, China also imposes carbon tariffs on the US imports. Production increases for all four regions. Therefore, their exports and production emissions increase. Emissions from the production in the US decrease by 4.1 percent. The last column shows the effect of imposing carbon tariffs individually by each region on the US real income. Changes in real income show that all regions gain at the expense of the US.

3.4.5 Retaliation of the US and Tariff War

In this scenario, taking the optimal carbon tariffs as given, the US optimally determines import tariffs against the imports from all committing regions. To see if the US has an incentive to retaliate by imposing import tariffs, welfare effects under two scenarios should be compared. Retaliatory tariffs increase the US real income by 1.44 percent and reduces the average real income in other regions by 0.61 percent. The US is better off by withdrawing from the Paris Agreement, bearing the cost of carbon tariffs and retaliating in response, compared to meeting its emission reduction targets under the Paris Agreement. Therefore, carbon tariffs are not effective instruments for enforcing the US to mitigate its emissions.

The retaliation of the US may trigger a worldwide tariff war with the other four regions that commit to meeting their emission reduction targets. I keep the non-cooperative nature of the national policy determination processes, therefore, in a worldwide tariff war scenario, committing regions do not form a coalition against the US. The Nash equilibrium in this scenario is found as follows: Each region observes the industry-level optimal non-cooperative tariffs imposed on its imports and choose its own optimal import tariffs, this process continues until welfare levels are maximized in all regions. Notice that, welfare includes the negative externality from global emissions. Therefore, in each decision step, regions observe the change in global emissions in response to the actions taken in the previous step and decide accordingly. Therefore, although the trade war occurs in a non-cooperative policy environment where all regions maximize welfare at the expense of other regions, increase in emissions is not to the advantage of any region. However, since the EU enjoys the largest benefits to its GDP from a unit reduction in global emissions, it is the region which values a unit reduction in global emissions the most. The results show that the median Nash tariffs is the lowest in the US with 12.55 percent. China imposes the largest median tariff on imports of all other regions with 44.63 percent. Canada's and the EU's median tariffs are 16.06 and 24.23 percent respectively. The tariff war results in a 3.1 percent decrease in the real income of the US. This is substantially larger than the compliance cost to the Paris Agreement. The real income levels decrease also in all other regions. All regions are much worse off in a tariff war situation compared to the Paris Agreement scenario. More importantly, all committing regions are worse off compared to the second scenario presented in section 3.4.2 in which they increase their emission reduction targets to make up for the withdrawal of the US.

3.5 Conclusion

This paper explores the interplay between environment and international trade related instruments in a non-cooperative policy environment where participation in a global climate agreement is voluntary and no punishment mechanism exists to enforce commitment. The main question that this paper aims to answer is whether a globally efficient response to climate change can be formed in a non-cooperative framework by employing carbon tariffs as an enforcement mechanism. When carbon tariffs are set in a way to mitigate the distortions that arise from cross-country differences in implicit costs of emissions, inducing participation is not possible. Unilaterally determined optimal carbon tariffs are more aggressive due to the imposing regions' willingness to influence the terms of trade in their favour. However, these are also not sufficient to encourage further mitigation in non-participating regions. Designing globally optimal carbon tariffs would require neutralizing the unilateral incentive to exploit terms-of-trade effects. Optimal carbon tariffs determined based on only environmental concerns would also be legally defensible under the environmental exceptions granted by the WTO. As Balistreri et al. (2016) has shown in a two-good, two-country environment, welfare maximizing carbon tariffs are too aggressive based on purely environmental concerns.

The theoretical framework developed by Ossa (2014) is extended to incorporate a cross-border production externality. To inform policy, the model is used to establish optimal carbon tariffs imposed on emissions embodied in imports (calculated based on the industry-level emission intensities of production of the importing regions). The policy experiment that involves the withdrawal of the US from the Paris Agreement indicates that imposing optimal carbon tariffs on the US imports results in retaliation. An alternative scenario worth investigating is changing the way tariff revenues are distributed. As has been discussed in the literature, transferring the tariff revenues to the US may induce cooperation in emission mitigation efforts. Other regions responses to the US retaliation through import tariffs may start a worldwide tariff war. A tariff war makes all regions worse off.

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Appendix A

Appendix to Chapter 1

A.1 Sample Trade and Navigation Tables

Tables presented here are two extracts from official statistics. The first one is from the Annual Statement of the Trade and Navigation of the United Kingdom with Foreign Countries and British Possessions in the Year 1861. This represents how international trade statistics were collected and presented after the decision to report current values of imports. The table provides detailed information on imported articles distinguished by the exporting country, total quantity imported from each exporter, the quantity retained for home consumption, total value of imports, the corresponding average prices, amount and rate of duty applied. The computed real values presented on these tables are actually the reported current values of imports.

The second table represents how the trade statistics were reported the period before the collection of current values. This table is from the Accounts Relating to Trade and Navigation. These tables report quantities imported, exported and retained for home consumption, and the corresponding duties for each article. Additional sources are necessary to determine import values.

PRINCIPAL ARTICLES.	COUNTRIES WHENCE IMPORTED.	QUANTITIES. Imported. In British Vessels.	QUANTITIES. Imported. In Foreign Vessels.	QUANTITIES. Imported. Total.	QUANTITIES. Entered for Home Consumption.	COMPUTED REAL VALUE. Total Imported.	COMPUTED REAL VALUE. Average Price Fixed for the Value.	DUTY. Gross Amount Received.	DUTY. Rate, and when Imposed.
		Proof Gallons.	Proof Gallons.	Proof Gallons.	Proof Gallons.	£	Per Gallon. £ s. d.	£	
Spirits: Rum	Holland	21,343	1,934	23,277	1,014	2,028	0 1 9	528	From British Possessions and from the Country of its Production: 10s. 2d. per Gallon - 17th July 1860. Not from the Country of its Production: 10s. 5d. per Gallon - 17th July 1860.
	France	19,880	16	19,896	711	1,741	0 1 9	371	
	Cuba	120,259	328,323	448,582	12,483	37,744	0 1 8	6,352	
	Dutch Guiana	53,257	14,260	67,517	9,740	5,770	0 1 9½	4,933	
	Mauritius	376,902	24,003	400,905	4,633	31,812	0 1 7 7/10	2,355	
	India, Singapore, and Ceylon	293,749	26,969	389,718	7,917	26,122	0 1 7¾	4,027	
	British North America	140,902	–	40,902	2,175	3,461	0 1 8¼	1,107	
	British West India Islands	2,919,966	218,918	3,138,884	1,238,043	255,532	0 2 3 3/10	620,251	
	British Guiana	3,002,756	38,437	3,041,193	1,850,389	324,769	0 1 9½	940,016	
	Other Parts	6,024	4,025	10,049	3,083	922	0 1 8¼	1,680	
	Mixed in Bond	–	–	–	322,987	–	–	164,315	
		7,455,936	658,985	8,114,922	3,452,575	790,010		1,755,555	
		Proof Gallons.	Proof Gallons.	Proof Gallons.	Proof Gallons.	£	Per Gallon. £ s. d.	£	
Brandy	Hamburg	22,846	724	23,570	1,917	3,578	0 3 0	999	10s. 5d. per Gallon - 17th July 1860.
	Holland	47,665	5,354	52,919	23,774	8,515	0 3 3	12,383	
	France	1,942,243	31,606	1,974,049	1,556,830	896,869	0 9 1	810,874	
	Australia	29,247	–	29,247	10,433	16,134	0 11 5	5,434	
	Other Parts	11,187	6,962	18,149	6,943	2,922	0 3 1	3,622	
		2,053,088	44,646	2,097,234	1,599,606	930,538		833,312	
		Proof Gallons.	Proof Gallons.	Proof Gallons.	Proof Gallons.	£	Per Gallon. £ s. d.	£	
Geneva	Holland	107,370	36,191	143,561	99,850	14,682	0 2 0½	52,008	10s. 5d. per Gallon - 17th July 1860.
	Other Parts	4,291	1,142	5,433	1,184	546		618	
		111,661	37,333	148,994	101,034	15,228		52,626	
		Proof Gallons.	Proof Gallons.	Proof Gallons.	Proof Gallons.	£	Per Gallon. £ s. d.	£	
Unenumerated, not Sweetened	Prussia	55,548	80,250	135,798	609	10,849	0 1 7½	317	From British Possessions: 10s. 2d. per Gallon - 17th July 1860. From Foreign Countries: 10s. 5d. per Gallon - 17th July 1860.
	Hamburg	156,293	45,053	201,366	6,076	17,285	0 1 8¾	3,633	
	United States, Northern Atlantic Ports	261	78,517	78,779	6,092	6,484	0 1 7¾	3,173	
	British North America	37,527	–	37,527	83	3,124	0 1 8	43	
	Other Parts	11,747	12,945	24,692	7,628	2,055	0 1 8	3,973	
		261,366	216,795	478,161	21,396	39,797		11,139	
		Flasks.	Flasks.	Flasks.	Flasks.	£	Per Flask. £ s. d.	£	
Water, Cologne, in Flasks	Holland	8,071	378	8,449	1,163	114	0 0 6	29	6d. per Flask - 17th July 1860. (When not in Flasks, 14s. per Gallon, as Perfumed Spirits.)
	Belgium	559	3,742	4,301	4,301	143		108	
	France	1,528	545	2,073	1,143	70		28	
	Other Parts	360	9	369	375	6		9	
		5,518	4,674	10,192	6,982	335		174	
		Gallons.	Gallons.	Gallons.	Gallons.	£	Shrub. Per Gal. £ s. d. / Other Kinds. Per Gal. £ s. d.	£	
Sweetened of All Kinds	Denmark	1,143	871	2,014	1,093	2,015	Shrub 0 3 0 / Other Kinds 1 0 0	766	Colonial: 10s. 2d. per Gallon - 17th July 1860. Foreign: 14s. per Gallon - 17th July 1860.
	Hamburg	1,491	196	1,687	923	1,686		287	
	Holland	9,876	3,961	13,837	8,305	13,836		5,877	
	Belgium	2,114	1,658	3,772	3,238	3,778		2,263	
	France	9,682	603	10,285	4,684	10,287		3,277	
	Austrian Territories	704	395	1,099	1,189	1,099		833	
	Channel Islands	2,118	–	2,118	686	2,121		481	
	Australia	1,260	–	1,260	7	1,260		5	
	British West India Islands	879	–	879	842	486		430	
	British Guiana	297	–	297	86	100		47	
	Other Parts	1,139	708	1,842	1,246	1,835		801	
		30,703	8,387	39,090	21,780	38,490		15,070	

DESCRIPTION OF MERCHANDIZE.		Quantities Imported.		Quantities Exported.		Quantities Retained for Home Consumption, and Charged with Duty.		RATES OF DUTY.		Net Revenue.	
		1849	1850	1849	1850	1849	1850	1849	1850	1849	1850
										£.	£.
Cotton Manufactures not made up, viz.:—											
Piece Goods of India	Pieces.	178,418	186,010	152,956	147,895	..	..	. . .	. . .	..	..
Entered at Value	£.	246,301	297,598	105,444	93,605	..	..	. . .	. . .	..	..
Cotton Manufactures wholly or in part made	,,	40,911	43,790	23,433	23,666	17,478	20,124	Of British Possessions, 5*l.*, Foreign, 10*l.* per cent. *ad valorem*	Same as in 1849.	1,769	2,040
Cotton Yarn	lbs.	413,478	905,966	375,367	777,957	..	..	. . .	. . .	..	..
Dyeing Stuffs, viz.:—											
Cochineal	Cwts.	18,254	22,451	14,179	9,859	..	..	. . .	. . .	..	..
Fustic	Tons	8,792	10,800	661	885	..	..	. . .	. . .	..	..
Gum Arabic	Cwts.	33,136	41,949	10,218	14,425	..	..	. . .	. . .	..	..
,, Senegal	,,	6,577	2,035	12	5	..	..	. . .	. . .	..	..
,, Animi and Copal	,,	4,315	4,888	3,704	2,819	..	..	. . .	. . .	..	..
,, Tragacanth	,,	314	526	240	128	..	..	. . .	. . .	..	..
Indigo	,,	81,332	70,482	69,179	54,108	..	..	. . .	. . .	..	..
Lac Dye	,,	13,585	18,124	7,053	6,583	..	..	. . .	. . .	..	..
Shellac	,,	14,786	20,245	9,537	10,294	..	..	. . .	. . .	..	..
Logwood	Tons	23,992	34,690	2,307	3,721	..	..	. . .	. . .	..	..
Madder	Cwts.	92,736	100,223	1,904	3,841	..	..	. . .	. . .	..	..
,, Root	,,	161,986	161,637	..	470	..	..	. . .	. . .	..	..
Nicaragua Wood	Tons	2,701	6,130	378	1,811	..	..	. . .	. . .	..	..
Safflower	Cwts.	10,452	13,462	4,940	4,397	..	..	. . .	. . .	..	..
Shumac	Tons	12,590	12,929	241	194	..	..	. . .	. . .	..	..
Smalts	lbs.	205,451	177,846	29,276	11,515	218,457	192,186	10*s.* per cwt.	Same as in 1849.	977	859
Valonia	Tons	16,671	12,526	3	17	..	..	. . .	. . .	..	..
Yellow Berries	Cwts.	7,761	8,290	835	514	..	..	. . .	. . .	..	..
Zaffres	,,	1,400	1,682	7	1	..	..	. . .	. . .	..	..
Elephants' Teeth	,,	7,292	9,162	1,289	2,562	..	..	. . .	. . .	..	..
Flax and Tow, or Codilla of Hemp and Flax	,,	1,806,673	1,822,918	49,227	42,913	..	..	. . .	. . .	..	..
Fruits, viz.:—											
* Apples, Raw	Bushels	323,719	467,629	82	..	323,614	467,625	Of British Possessions 2*d.*, other parts 6*d.* per bushel	Ditto	8,506	12,327
Almonds, Bitter	Cwts.	6,141	5,729	2,866	1,939	..	..	. . .	. . .	..	..
* ,, not Bitter	,,	25,897	16,988	14,087	7,253	9,624	8,368	Jordan 25*s.*, other sorts 10*s.* per cwt.	Ditto	7,207	6,594
Chesnuts	Bushels	74,849	88,287	303	749	..	..	. . .	. . .	..	..
* Currants	Cwts.	457,592	429,667	21,195	18,003	433,044	405,077	15*s.* per cwt.	Ditto	310,986	319,030
* Figs	,,	39,273	33,829	1,150	4,193	30,844	32,976	15*s.* per cwt.	Ditto	24,452	25,982
* Grapes	£.	28,202	31,259	145	125	28,057	31,134	5*l.* per cent., *ad valorem*	Ditto	1,477	1,633
* Oranges and Lemons	Chests or Boxes.	361,412	402,748	5,271	1,280	295,774	345,562	Not exceeding 5,000 cubic inches 2*s.* 6*d.*; 5,000 to 7,300, 3*s.* 9*d.*; 7,300 to 14,000, 7*s.* 6*d.* per chest, or 75*l.* per cent. *ad valorem*	Ditto	64,679	75,408
	£.	3,094	3,568	15	138	10,749	12,960				
* Plums, Dried, or Preserved, except in Sugar	Cwts.	376	340	119	73	237	331	1*l.* 7*s.* 6*d.* per cwt.	Ditto	343	487
* ,, French or Prunellors	,,	3,594	4,038	137	288	3,224	3,694	1*l.* per cwt.	Ditto	3,415	3,858
* Prunes	,,	12,333	11,479	1,393	1,240	14,586	16,609	7*s.* per cwt.	Ditto	5,360	6,100
* Raisins	,,	209,180	275,689	19,351	13,325	193,315	217,808	Of British Possessions 7*s.* 6*d.*; Foreign, 15*s.* per cwt.	Ditto	151,805	171,653
* Small Nuts	Bushels	134,292	199,278	2,349	2,557	130,986	188,882	2*s.* per bushel	Ditto	13,614	19,786
* Walnuts	,,	45,950	37,724	1,030	961	44,406	37,615	2*s.* per bushel	Ditto	4,856	4,092

Appendix B

Appendix to Chapter 2

B.1 Derivation of International Trade Shares and Prices

The unit cost of purchasing good ω from region i is $p^j_{ni}(\omega) = \frac{c^j_i d^j_{ni}}{z^j_i(\omega)}$. The random productivity draws have a Fréchet distribution given by $F(z) = e^{-T^j_n z^{-\theta^j}}$, using these I can derive the distribution of prices in region n:

$$
\begin{aligned}
F_i(z) &= \Pr\Big[z^j_n(\omega) \leqslant z\Big] \\
&= \Pr\left[\frac{c^j_i d^j_{ni}}{p^j_{ni}(\omega)} \leqslant z\right] \\
&= \Pr\left[\frac{c^j_i d^j_{ni}}{z} \leqslant p^j_{ni}(\omega)\right] \\
&= \Pr\Big[p \leqslant p^j_{ni}(\omega)\Big] \\
&= 1 - \Pr\Big[p^j_{ni}(\omega) \leqslant p\Big]
\end{aligned}
$$

$$= 1 - G_{ni}(p)$$

$$G_{ni}(p) = 1 - F\left(\frac{c_i^j d_{ni}^j}{p}\right)$$

$$= 1 - e^{-A_{ni}^j p^{\theta^j}} \tag{B.1}$$

where $A_{ni}^j = T_i^j \ (c_i^j d_{ni}^j)^{-\theta^j}$.

Only the intermediate good ω with the lowest price is purchased in region n. Given equation (B.1), the distribution of the minimum cost of delivery of good ω from region i to region n, $p_n^j(\omega)$, can be determined by

$$G_n(p) = \Pr\left[\min_{i \in \{1,N\}} \left\{p_{ni}^j(\omega)\right\} \leqslant p\right]$$

$$= 1 - \Pr\left[\min_{i \in \{1,N\}} \left\{p_{ni}^j(\omega)\right\} \geqslant p\right]$$

$$= 1 - \Pr\left[p_{n1}^j(\omega) \geqslant p\right] \Pr\left[p_{n2}^j(\omega) \geqslant p\right] ... \Pr\left[p_{nN}^j(\omega) \geqslant p\right]$$

$$= 1 - \prod_{i=1}^{N} \Pr\left[p_{ni}^j(\omega) \geqslant p\right]$$

$$= 1 - \prod_{i=1}^{N} (1 - G_{ni}(p))$$

$$= 1 - e^{-\Phi_n^j p^{\theta^j}} \tag{B.2}$$

where $\Phi_n^j = \sum_{i=1}^N A_{ni}^j = \sum_{i=1}^N T_i^j \ (c_i^j d_{ni}^j)^{-\theta^j}$. The condition $d_{ni}^j = \infty$ can be imposed to model a non-tradable industry, for these industries $\Phi_n^j = T_n^j \ (c_n^j)^{-\theta^j}$ for all $i \neq n$.

The distribution of prices can be used to drive the aggregate price index in region n. The price index is equal to

$$P_n^j = \left[\int_0^1 p_n^j(\omega)^{1-\sigma^j} d\omega \right]^{1/(1-\sigma^j)}$$

which can be expressed as

$$P_n^j = \left[\int p^{1-\sigma^j} g_n(p)\ dp \right]^{1/(1-\sigma^j)}$$

where $g(p)$ is the density of p, and can be derived from equation (B.2). Substituting this yields,

$$P_n^j = \left[\int p^{1-\sigma^j} e^{-\Phi_n^j p^{\theta^j}} \Phi_n^j \theta^j p^{\theta^j - 1}\ dp \right]^{1/(1-\sigma^j)}$$

With a change of variables $u = \Phi_n^j p^{\theta^j}$ and $du = \Phi_n^j \theta^j p^{\theta^j - 1} dp$, I obtain the price index for industry j goods in region n

$$\begin{aligned} P_n^j &= \left[\int u^{\frac{1-\sigma^j}{\theta^j}} {\Phi_n^j}^{\frac{\sigma^j - 1}{\theta^j}}\ e^{-u}\ du \right]^{1/(1-\sigma^j)} \\ &= {\Phi_n^j}^{-\frac{1}{\theta^j}} \left[\int u^{\frac{1-\sigma^j}{\theta^j}}\ e^{-u}\ du \right]^{1/(1-\sigma^j)} \\ &= \eta^j {\Phi_n^j}^{-\frac{1}{\theta^j}} \end{aligned}$$

where $\eta^j = \Gamma(1 + \frac{1-\sigma^j}{\theta^j})^{1/(1-\sigma^j)}$ is a gamma function. The restriction $1 + \theta^j > \sigma^j$ assures that the gamma function is defined. If a industry is not traded $P_n^j = \eta^j {T_n^j}^{-1/\theta^j} c_n^j$.

The share of region n's expenditures allocated to the goods in industry j from region i is equal to the share of industry j goods for which region i is the lowest cost supplier. The probability that region i is the lowest cost supplier of of good ω is given by

$$\pi_{ni}^j = \frac{X_{ni}^j}{X_n^j} = \Pr\left[p_{ni}^j(\omega) \leqslant \min_{h \neq i} \{ p_{nh}^j(\omega) \} \right]$$

Using the distributions of prices in (B.1) and (B.2), the trade share can be obtained as

$$\pi_{ni}^{j} = \frac{T_i^j \ (c_i^j d_{ni}^j)^{-\theta^j}}{\sum_{i=1}^{N} T_i^j \ (c_i^j d_{ni}^j)^{-\theta^j}} \tag{B.3}$$

B.2 Additional Tables

Table B.1: Trade Elasticities

Industry	θ^j
Agriculture and Forestry	8.11
Mining	15.72
Food and Textiles	4.56
Wood	10.83
Paper	9.07
Chemicals	19.16
Metals	5.02
Machinery and Equipment	6.19
Manufacturing, n.e.c.	5.00
Utilities	5.00
Construction	5.00
Wholesale and Retail	5.00
Hotels and Restaurants	5.00
Transportation	5.00
Communication	5.00
Finance	5.00
Computer and Related Activities	5.00
Other Business Activities	5.00
Public Administration	5.00
Education	5.00
Health and Social	5.00
Other Services	5.00

Source: Caliendo and Parro (2015)

Table B.2: Industry Emissions, by Province and Territory (kt of CO_2)

Industry	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK	YT
Agriculture and Forestry	1,702	1,507	762	187	124	165	1,691	66	1,111	1,347	2
Mining	28,700	1,670	155	257	1,073	135	730	2	910	3,823	29
Food and Textiles	69	470	428	170	65	117	1,401	77	935	299	0.28
Wood	199	428	19	58	2	23	136	0.38	184	15	0.16
Paper	468	1,140	129	418	12	189	858	4	1,189	67	0.18
Chemicals	46,677	12,911	1,292	2,547	1,806	523	7,981	3	6,240	7,281	0.06
Metals	541	2,620	141	56	3	20	50,527	1	9,409	182	0.14
Machinery and Equipment	636	263	221	32	12	41	1,221	4	534	113	1
Manufacturing, n.e.c.	31	19	7	12	1	1	48	0.27	29	4	0.22
Utilities	49,352	891	127	5,400	1,413	8,522	14,776	2	641	15,739	12
Construction	3,996	1,207	359	132	155	105	2,010	18	1,744	625	20
Wholesale and Retail	2,346	858	381	116	58	188	4,207	14	1,962	475	8
Hotels and Restaurants	137	130	58	18	10	32	362	4	197	48	3
Transportation	5,992	6,762	1,769	648	469	766	12,332	83	5,435	1,344	51
Communication	221	228	60	35	12	36	977	3	344	65	2
Finance	3,010	1,016	983	124	102	231	3,711	90	1,824	541	17
Computer and Related Activities	14	8	3	3	0.46	5	21	0.40	23	3	0.05
Other Business Activities	796	415	118	74	33	68	1,641	9	730	104	7
Public Administration	1,693	474	249	177	57	230	2,995	17	851	546	23
Education	1,303	361	123	23	34	58	1,274	8	568	169	3
Health and Social	349	270	167	67	61	83	1,480	12	288	161	5
Other Services	891	457	105	31	19	58	1,523	6	652	143	3

Notes: For sources, see text.

Appendix C

Appendix to Chapter 3

C.1 Eliminating Aggregate Trade Deficits

Table C.1 presents the predicted changes in exports and imports resulting from an elimination of aggregate trade imbalances. The first column displays the trade deficits in the raw data as a share of total trade. The second and third columns show the effects of the procedure described in sector 3.2. Imports and exports change substantially to eliminate these imbalances. I use this purged data in the quantitative applications presented in section 3.4.

Table C.1: Effects of Eliminating Trade Deficits

Region	Net Exports (in %)	Imports (in %$\triangle$)	Exports (in %$\triangle$)
Canada	-0.44	-2.41	-1.55
China	0.88	2.35	0.57
EU	-1.21	-2.37	0.02
RoW	1.79	3.93	0.28
USA	-7.00	-15.27	-2.69

Note: Displays the effects of the procedure explained in section 3.2 on the values of imports and exports. The first column lists the net exports as a share of total trade for each region in the raw data calculated as $100 \times \left(\frac{exports-imports}{exports+imports}\right)$. The second and third columns display the percentage changes in imports and exports as a results of this procedure to eliminate trade deficits.

C.2 Additional Tables

Table C.2: Trade-weighted Factual Tariffs, by Region and Industry (in %)

Industry	CAN	CHN	EU	USA	RoW
Agriculture	0.03	0.08	0.03	0.14	0.03
Mining	0.00	0.00	0.01	0.01	0.01
Food Products	0.17	0.13	0.09	0.13	0.06
Textile	0.13	0.10	0.10	0.08	0.11
Wood Products	0.02	0.03	0.02	0.04	0.02
Paper and Printing	0.01	0.02	0.00	0.04	0.01
Petroleum	0.01	0.05	0.02	0.03	0.06
Chemicals	0.02	0.06	0.03	0.04	0.02
Plastic Products	0.04	0.08	0.05	0.07	0.04
Mineral Products	0.02	0.11	0.04	0.07	0.04
Metals	0.02	0.10	0.04	0.11	0.04
Machinery and Equipment	0.01	0.06	0.02	0.04	0.01
Electrical and Optical	0.02	0.12	0.05	0.09	0.04
Transport	0.07	0.22	0.09	0.11	0.04
Other	0.04	0.09	0.01	0.04	0.01

Table C.3: Trade-weighted Average Carbon Tariffs on US Imports, by Region and Industry (in %)

Industry	CAN	CHN	EU	USA	RoW
Agriculture	0.11	0	0.11	0	0.13
Mining	0.18	0	0.04	0	0.10
Food Products	0.10	0	0.03	0	0.05
Textile	0.01	0	0.01	0	0.02
Wood Products	0.15	0	0.04	0	0.06
Paper and Printing	0.09	0	0.07	0	0.04
Petroleum	0.44	0	0.18	0	0.31
Chemicals	0.24	0	0.28	0	0.18
Plastic Products	0.06	0	0.05	0	0.24
Mineral Products	0.03	0	0.15	0	0.14
Metals	0.11	0	0.08	0	0.25
Machinery and Equipment	0.03	0	0.03	0	0.03
Electrical and Optical	0.02	0	0.03	0	0.09
Transport	0.03	0	0.04	0	0.02
Other	0.03	0	0.03	0	0.06

Table C.4: Trade-weighted Average Carbon Tariffs, by Region and Industry (in %)

Industry	CAN	CHN	EU	USA	RoW
Agriculture	0.12	0	2.64	0.02	0.18
Mining	0.18	0	3.51	0.01	0.15
Food Products	0.13	0	1.39	0.05	0.11
Textile	0.15	0	1.09	0.41	0.41
Wood Products	0.23	0	0.98	0.41	0.21
Paper and Printing	0.11	0	1.31	0.15	0.09
Petroleum	0.44	0	11.96	0.03	0.46
Chemicals	0.27	0	2.74	0.10	0.48
Plastic Products	0.09	0	0.78	0.06	0.45
Mineral Products	0.06	0	7.17	1.42	1.87
Metals	0.18	0	3.07	0.12	0.88
Machinery and Equipment	0.05	0	0.29	0.06	0.08
Electrical and Optical	0.08	0	0.31	0.04	0.27
Transport	0.03	0	0.34	0.02	0.06
Other	0.13	0	0.69	0.07	0.57

Table C.5: List of Industries

Industry	Description	ISIC Rev. 3
Agriculture	Agriculture, forestry and fishing	1-5
Mining	Mining and quarrying	10-14
Food Products	Food products, beverages and tobacco	15-16
Textile	Textiles, textile products, footwear and leather	17-19
Wood Products	Wood, wood products and cork	20
Paper and Printing	Pulp, paper, paper products, printing and publishing	21-22
Petroleum	Coke, refined petroleum and nuclear fuel	23
Chemicals	Chemicals	24
Plastic Products	Rubber and plastic products	25
Mineral Products	Other non-metallic mineral products	26
Metals	Basic metals and metal products	27-28
Machinery and Equipment	Machinery and equipment n.e.c.	29
Electrical and Optical	Office equipment, electrical machinery and medical instruments	30-33
Transport	Motor vehicles, and other transport equipment	34-35
Other	Manufacturing n.e.c.	36-37