TOPICS IN FOREST PRODUCT MODELLING:
THE ECONOMICS OF BIOENERGY PRODUCT EXPORTS FROM FORESTS

by

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ABSTRACT

As many countries turn to biomass for energy production to combat climate change, the effects on the global forest products industry remains for the most part, unknown. Although the individual studies of this thesis stand on their own, the results share a common theme of examining economic issues surrounding a greater reliance on energy derived from forests.

Chapter 1 presents the development and application of a non-linear programming model of global forest product trade used to assess the economic impact of an increase in global bioenergy demand. The results of the study indicate that increased global bioenergy demand will result in increased production of lumber and plywood, but outputs for fibreboard, particleboard and pulp will decline. In addition, renewable energy policies promoting bioenergy cause wood pellet prices to rise which could undermine the effectiveness of such policies.

The European Union (EU) has implemented the most aggressive renewable energy policies in the world, and as a result, has quickly become a global leader in bioenergy production. To meet their targets, the EU is expected to import an unprecedented amount of fibre from timber rich regions, causing ripple effects throughout the global forest products industry. Chapter 2 discusses such EU policies, utilizing the developed global forest products trade model. Results indicate increased EU bioenergy demand is welfare enhancing to the global forest products industry as a whole, although there are winners and losers.

Chapter 3 presents another important issue regarding increased bioenergy demand, that is, the supply of fibre is a limiting factor for its viability as an energy source. The chapter discusses the development and application of an electrical grid model of Alberta that is linked to a fibre transportation model of Alberta and British Columbia. Results show that proximity to a wood pellet producer is critical in the economic viability of retrofitting coal-fired power plants to co-fire with biomass.

Finally, the increasing reliance on bioenergy as a fossil fuel substitute depends critically on the acceptance that CO_2 release associated with combustion is offset by the re-growth of the forest. Chapter 4 provides a discussion of this issue, sighting the significance of the timeline in CO_2 release and absorption. If we deem climate change an urgent matter, we may give more weight to current reductions in atmospheric CO_2, eroding the carbon neutrality of biomass

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Chapter 1

INTRODUCTION

Global climate change has evolved as a major scientific and public policy issue. Recognized as a significant and lasting change in weather patterns[1], climate change may lead to increased temperatures, rising sea levels, stronger storms and increased risk of droughts, fires and floods. In turn, these can have significant impacts on functioning ecosystems, the viability of wildlife, as well as human welfare.

With this in mind, mitigating the effects of climate change has emerged as a prominent international issue. There have been numerous attempts aimed at addressing climate change, with the most significant being the Intergovernmental Panel on Climate Change (IPCC). The IPCC works under the umbrella of the United Nations Framework Convention on Climate Change (UNFCCC), an international environmental treaty signed in 1992 at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil. Although the UNFCCC treaty itself does not set or enforce limits on greenhouse gas emissions, the objective of the treaty is to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UNFCCC, 1992). In turn, the IPCC produces assessments in line with the UNFCCC objective, accepted as the international authority on climate change.

Relying on the forestry sector to combat climate change gained widespread recognition when the IPCC released its *Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006). In particular, *Volume 4 – Agriculture, Forestry and Other Land Use* (AFOLU) sector (previously

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[1] A general definition of *climate change* is a change in the statistical properties of long-term weather records; short-term fluctuations in weather, such as El Niño, do not represent climate change.

the LULUCF[2] sector), outlines the IPCC guidelines for accounting for carbon dioxide (CO_2) emissions from the combustion of biomass for energy purposes. Although the IPCC never made any assumptions about the carbon neutrality of biomass, certain accounting practices allow biomass combustion to be recorded as zero emissions. For one, CO_2 emissions associated with biomass combustion for energy purposes are not recorded in the Energy sector, as they are already accounted for in the AFOLU sector. Alternatively, the carbon stock released during the harvest of annual crops is assumed to be offset from the subsequent re-growth, so no net CO_2 emissions are reported. Together, these accounting practices open the door for biomass to be substituted for fossil fuels in order to reduce the CO_2 emissions associated with producing energy.

1.1 Biomass and Climate Change

A natural carbon flux and exchange occurs between a forest and the atmosphere, whereby a forested ecosystem plays an important role in the global carbon cycle by sequestering and storing carbon. Before we proceed, it is important to understand how carbon is stored in forests. Through photosynthesis, forests remove CO_2 from the atmosphere by utilizing energy from the sun to convert water and CO_2 to sugars and oxygen. The sugars are used to produce the carbon-based cellulose, the primary structural component of the tree. As a result, carbon is removed from the atmosphere and stored in the roots, stems, and leaves. As a tree grows, it will continue to absorb more and more carbon.

When the tree experiences natural mortality, the stored carbon is gradually released through decomposition. Much of the carbon is still contained within a fallen tree, where the soil organic matter eventually breaks down and the original carbon that was fixed during photosynthesis is returned to the atmosphere. In the absence of harvesting, the cycling of carbon between a forest ecosystem and the atmosphere continues until the forest reaches an old growth state, which varies by species, the climate, soil chemistry and other factors.

When a tree is harvested, much of the original carbon is removed from the ecosystem and

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[2] Land Use, Land Use Change and Forestry

stored in the wood. Depending on the use, the carbon can be held for varying lengths of time. If the wood is used in construction materials, it may be stored for centuries. If it is used for paper products, the carbon may be stored for a shorter period of time until it is incinerated or discarded to decompose in a landfill. Finally, if the wood is used for fuel or energy, the carbon is released immediately.

It is this latter use of wood that is of particular interest to this thesis. There exists great potential for forests to play an even larger role in global energy production as developed countries utilize the natural carbon flux of the forest to mitigate contributions to atmospheric CO_2. The IPCC Guidelines draw support from the natural carbon flux that occurs in the forested ecosystem, allowing for biomass to be substituted for fossil fuels to lower the CO_2-intensity of energy production.

1.2 Challenges

The real growth potential for bioenergy comes from 'modern' usage[3] as opposed to primitive forms, as seen in many developing countries around the world. The combination of efficiency gains due to modern bioenergy and the current international policy frameworks imply a trend towards a greater reliance on energy from biomass. This will inevitably include a replacement of older technologies with modern bioenergy plants, as well as an increasing reliance on large-scale international trading of bioenergy commodities (Lamers et al., 2012).

This increased reliance on bioenergy to combat climate change is not without its challenges. As many countries are turning to wood pellets for commercial energy production, the effects on the global forest industry remains for the most part, unknown. The raw materials used to produce pellets have traditionally come from waste materials from harvest as well as sawmilling residues (i.e. sawdust, planer shavings). However, increased global bioenergy demand may result in fibre distributed away from traditional users (i.e. fibreboard, pulp and paper), towards the production of bioenergy products like pellets (Stennes et al. 2010). The

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[3] Modern usage bioenergy refers to higher conversion efficiency meant for large-scale energy production. Often, biomass is converted to higher value and more energy intensive forms (e.g. wood pellets).

interconnection between wood pellets and the rest of the wood products industry is complex, while the impacts of increased pellet demand remain unanswered. If demand becomes significant enough, growing trees in plantations as well as dedicated removals from harvested sites may well emerge as economical means of supplying fibre. In many cases, the feasibility of modern bioenergy still depends on proximity to low cost, sustainable supplies of fibre.

As a result of substantial government support to reduce atmospheric CO_2 emissions, many countries are importing bioenergy products from timber rich regions. Perhaps the greatest example of this is occurring in the European Union (EU). With the IPCC carbon accounting guidelines in place, EU countries are turning to carbon neutral biomass to comply with their aggressive renewable energy targets (European Commission 2013; 2014). International imports of wood pellets to be used in EU coal-fired power plants have been increasing exponentially in the past decade, while the effect on the global wood products industry is still uncertain. Further, government support encouraging bioenergy may push up the price of wood pellets, undermining the effectiveness of such policies.

A number of other issues deserve consideration, but it is the urgency to deal with climate change that may prove most challenging to bioenergy. Leaning on the IPCC carbon accounting guidelines, many countries are turning to biomass to mitigate CO_2 emissions from energy production. As carbon released today from biomass combustion is sequestered by the subsequent re-growth of the forest, many accept that bioenergy is a carbon neutral energy source. Yet, this acceptance relies on the fact that we have no time preference for combating global warming. That is, it doesn't matter if atmospheric CO_2 contributions are reduced today, in five years, or a thousand years from now. The degree to which greater urgency to deal with global climate change erodes the acceptance of biomass as a 'zero carbon' energy source deserves appropriate attention as countries race to transition their energy grids to modern bioenergy.

1.3 Thesis Structure

This thesis is a collection of four studies, tied together with this introductory chapter and a concluding chapter. Chapter 2 presents the results of a non-linear programming model of global forest product trade (described in the Appendix) used to assess the economic impact of an increase in global bioenergy demand. The results indicate that increased global bioenergy demand will lead to a rise in production of lumber and plywood, but outputs for fibreboard, particleboard and pulp will decline. In addition, the results show that renewable energy policies promoting bioenergy cause wood pellet prices to rise, which could undermine the effectiveness of such policies.

The European Union (EU) has implemented the most aggressive renewable energy policies in the world, and as a result, has quickly become a global leader in bioenergy production. To meet their targets, the EU is expected to import an unprecedented amount of fibre from timber rich regions, even though it is not yet known how this will impact the global forest products industry. Chapter 3 discusses such EU policies, utilizing the global forest products trade model as described in the Appendix. The results of the chapter suggest that increased EU bioenergy demand is welfare enhancing to the global forest products industry as a whole, although there are winners and losers.

Chapter 4 presents another important issue regarding bioenergy, that is, the supply of fibre is often a limiting factor for its viability as an energy source. The chapter discusses the development and application of an electrical grid model of Alberta that is linked to a fibre transportation model of Alberta and British Columbia. The results show that proximity to a wood pellet producer is critical in the economic viability of retrofitting coal-fired power plants to co-fire with biomass.

The increasing reliance on bioenergy as a fossil fuel substitute depends critically on the acceptance that CO_2 release associated with combustion is offset by the subsequent re-growth of the forest. Chapter 5 provides a discussion of this issue, sighting the significance of the timeline in CO_2 release and absorption. If we deem climate change as an urgent matter, we may give more weight to current reductions in atmospheric CO_2, undermining biomass as a ‘zero emissions’ energy source.

The concluding chapter summarizes the main findings and discusses the broad policy implications, followed by a short discussion looking to future work. To complete the thesis, a detailed Appendix is provided that describes the global forest products trade model employed in Chapters 2 and 3.

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Chapter 2

ECONOMIC CONSEQUENCES OF INCREASED BIOENERGY DEMAND[4]

2.1 Introduction

Countries around the world are legislating ever more stringent renewable energy policies, with European countries leading the way. As a result of aggressive government intervention, the energy sector will need to transition to sources that have much lower carbon dioxide (CO_2) emissions. While wind turbines and solar panels have traditionally been the face of such efforts, countries will need to rely to a much greater extent on biomass to meet their renewable energy targets. In particular, utilities are increasingly looking to co-fire biomass with coal to reduce the CO_2-emissions intensity of coal plants, as required in the legislation of some countries (e.g., Canada, U.S.). Consequently, some 230 coal-fired power plants worldwide have been retrofitted to co-fire with biomass on a commercial basis (IEA-ETSAP and IRENA Brief E21, 2013). As the number of coal plants converting to burn biomass increases, it has become worthwhile for timber-rich regions to ramp up production of wood biomass for energy purposes, especially production of wood pellets. As a result, global wood pellet production has increased from 1.7 million tonnes (Mt) in 2000 to 15.7 Mt in 2010, and is projected to reach 38 Mt by 2020 (Lamers et al., 2012).

Co-firing biomass in existing coal-fired power plants is appealing due to the low incremental investment required to retrofit established facilities and because energy produced

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[4] A version of this chapter has been published in The Forestry Chronicle **90**(5): 636-642.

from biomass is considered to be carbon neutral (IPCC 2006). Since much of the biomass to produce pellets comes from logs, the demand for wood fibre by the energy sector will impact the manufacture of wood products (lumber, plywood, pulp, oriented strand board, medium density fibre board, etc.). To the extent that wood pellets and lumber are joint outputs, an increase in the demand for sawmill residues will increase the value of logs and thereby the demand for logs. Importantly, increased demand for wood pellets will enhance competition for residual fibre, thereby impacting other wood processing sectors. In this chapter, we consider the impacts of changes in the demand for wood pellets on the overall forest sector.

Few studies have attempted to assess the implications of increased bioenergy demand on the global forest products sector. Exceptions include Raunikar et al. (2010) and Buongiorno et al. (2011), but these authors have looked specifically at roundwood use for cooking, heating or power production, collectively referred to as fuelwood. The authors conclude that increased bioenergy (fuelwood) demand results in the convergence of fuelwood and industrial roundwood prices, while the prices of other forest products, including sawnwood and panels, would rise significantly. In addition, an increase in bioenergy demand could result in an increase in the price of forestland, causing forest area to expand (Ince et al., 2011, 2012; Moiseyev et al., 2011).

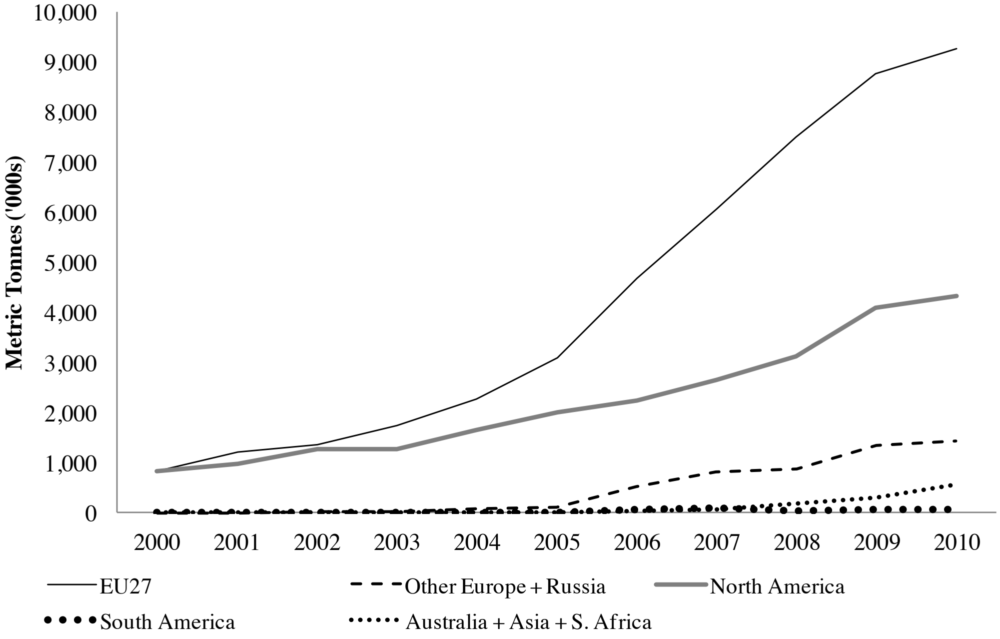

Figure 2.1: Global Wood Pellet Production, 2000-2010 (Source: FAO, 2013)

The focus on fuelwood is misplaced, however, because the vast majority of fuelwood is used primarily in developing countries for subsistence – as a fuel for heating and cooking (FAO, 2014). In contrast, the recent rise in bioenergy demand is a rich-country phenomenon that is characterized by increased international trade in wood products and is met by residuals from downstream manufacturing, much of which is increasingly converted to wood pellets (Figure 2.1).

In this chapter, we analyze increased bioenergy demand sourced directly from the harvest of energy biomass and indirectly as residues from commercial roundwood harvests and manufacturing. A rising portion of this fibre is then processed into wood pellets as opposed to fuelwood. Given that many countries provide significant subsidies for bioenergy, understanding the true costs and benefits associated with such a policy is critical. Timber rich regions are likely to be significantly impacted by such a policy, as it results in adjustments to their production, consumption and trade patterns.

2.2 Methods

2.2.1 Vertical and Horizontal Market Integration

To determine how increased demand for wood pellets impacts the rest of the forest products industry, we consider an integrated coniferous wood products trade model with upstream producers of logs and downstream users of wood products. The theoretical framework of the trade model, data sources and numerical implementation are described in the Appendix. The theoretical foundations describe the costs, benefits and re-distributional impacts of any given policy – i.e., the economic surpluses, or welfare areas, that are measured. These consist of the areas under demand and supply functions, with the former constituting benefits and the latter costs. While the model in essence calculates the familiar consumer and producer surpluses, several assumptions are needed to make the model tractable; these are briefly described in what follows.

Downstream users include furniture makers, construction firms, pulp producers, electricity providers, and other industries that rely on wood products. The demands for wood products are derived demands from these downstream industries, while the demand for logs is derived from the demands of the log processing sector. In our model, the wood-processing sector consists of sawmilling (lumber), plywood manufacture, manufacture of particleboard and fibreboard, pulp production, and wood pellet production. In order to measure welfare changes that result from changes in policy, it is necessary to make some assumptions about markets upstream from log production (e.g., logging trucks, chain saws, fuel, labour, other logging equipment, silvicultural inputs) and downstream from lumber, plywood, board, pulp and wood pellet production (e.g., construction, furniture, paper and electricity). In particular, we assume that producers of logs face a perfectly elastic supply of inputs (fixed factor prices) and downstream users of manufactured wood products face a perfectly elastic demand for their products. That is, changes in the output of logs cannot affect the prices that log producers' pay for inputs; likewise, changes in prices of lumber and residuals cannot impact housing, paper, energy, furniture and other final output prices. Finally, it is assumed that prices of other goods and service in the economy are not affected by changes in wood product prices.

The key to the current model is the availability of coniferous logs. Two categories of processors are assumed – those that directly affect the demand for logs and those that do so indirectly. Sawmilling is assumed to impact the log market directly through the production of three kinds of products – lumber, plywood and wood residuals (or residues). Manufacturers of particleboard, fibreboard, pulp and wood pellets (the four other wood processors in our model) can use whole logs but primarily rely on residues from sawmills. Logs are simply too valuable in the production of structural lumber and plywood to be used in the production of other wood products, although there are exceptions (e.g., pulp logs are not normally used for lumber). These secondary users of logs have an indirect impact on the demand for (saw) logs because, if the prices of secondary products rise, logs become more valuable to the sawmilling sector. This is because residues are a joint product with lumber and plywood. That is, if one of the products from sawmilling (residues) increases in price, sawmills will increase their demand for logs at the margin. Thus, whether directly, or indirectly, the demand for logs is derived through the demand for these downstream products, with the price of logs increasing with the demand for downstream products:

$$\frac{\partial D_{\log}(P_{\log};p_k)}{\partial P_{\log}} < 0 \text{ and } \frac{\partial D_{\log}(P_{\log};p_k)}{\partial p_k} > 0, \tag{2.1}$$

$$k \in \{\text{lumber, plywood, particleboard, fibreboard, pulp, pellets}\}$$

where $D_{log}(P_{log};\, p_k)$ is the derived demand for logs by downstream producers of wood product *k* as a function of the price of *k*. Relation (2.1) indicates that the price of logs (P_{log}) will rise if the supply of logs is upward sloping, which is the case here. An increase in the price of logs will, in turn, shift the supply curve for downstream products upwards (reducing supply):

$$\frac{\partial S_k(p_k;P_{\log})}{\partial p_k} > 0 \text{ and } \frac{\partial S_k(p_k;P_{\log})}{\partial P_{\log}} < 0, \forall k, \tag{2.2}$$

where S_k is the supply curve for downstream wood product *k*. Thus, an increase in the demand for any wood product *k* will increase the price of all other wood products (including the original product whose demand increased).

Suppose now that there is an increase in the demand for wood pellets as a result of subsidies to their use in coal-fired power plants (or due to legislation mandating their use in coal plants). This leads to an increase in the demand for sawmill residuals that, in turn, leads to somewhat greater output of lumber and increased demand for logs. It will also increase the demand for roadside wastes associated with harvest operations, but whether this increases removal of such wastes is questionable and a separate issue not considered here (see Niquidet et al., 2012). More importantly, an increase in the demand for wood pellets will result in the re-direction of residual fibre away from particleboard, fibreboard and pulp production[5] to its use in coal plants (Stennes et al., 2010). These products are competitive with wood pellets, because fibre used to produce wood pellets cannot be used to produce particleboard, fibreboard or pulp. Therefore, $\frac{\partial S(p_s;p_c,P_{\log})}{\partial p_{pellet}} < 0, \forall s \in \{\text{particleboard, fibreboard, pulp}\}, c \in \{\text{lumber, plywood}\}.$

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[5] In some instances pulp may be a primary product, and as a result, could be complementary in production (i.e. Western Canada). As this does not extend to most other regions of the world, it is assumed in this research that pulp is competitive in production.

The impact of an increase in the demand for wood pellets on lumber and plywood markets is less certain. On the one hand, a higher price of wood pellets increases the value of logs through an increase in the derived demand for logs as indicated in relation (2.1). This inevitably leads to a reduction in the supply of lumber and plywood through relation (2.2). On the other hand, increased wood pellet demand also creates higher value for the wood residues produced jointly in the sawmilling sector. Because producers of lumber and plywood are able to sell wood residuals at a higher price, this lowers the cost of sawmilling, thereby increasing the supply for products that are complementary in production: $\frac{\partial S(p_c; p_s, P_{\log})}{\partial p_{pellet}} > 0$. The extent to which one effect dominates the other depends on the cross-price elasticities of demand between pellets and lumber, and between lumber and logs. Thus, it is an empirical issue.

By considering the interactions between the various horizontal and vertical markets, shifts in any one market may affect the others. In this analysis, a significant increase in wood pellet demand may increase competition for fibre (logs), resulting in significant impacts in the markets for other traditional wood products (see Raunikar et al., 2010; Buongiorno et al., 2011; Ince et al., 2011, 2012; Moiseyev et al., 2011). It should be emphasized, however, that wood product markets are not only connected through these vertical and horizontal chains within a given jurisdiction, but also among jurisdictions through international trade. Unravelling the impacts of increased wood pellet demand will ultimately require international considerations.

2.2.2 Global Trade Modelling

To determine the welfare (cost-benefit) impacts of increased global demand for wood pellets, we employ a global trade model for coniferous forest products that is described in detail in the Appendix. The model assumes that, while changes in countries' forest policies will affect prices of forest products, they have no discernible impact on the relative prices of goods and services elsewhere in the economy. As a spatial price equilibrium model, the trade model assumes that, in the absence of trade barriers and transaction costs, prices would be the same in every region as a result of spatial arbitrage. Differences in prices between regions are thus assumed to be the result of transaction costs, and include costs associated with transporting goods (e.g., freight, insurance, exchange rate conversion fees), plus tariffs and other non-tariff barriers. The numerical trade model is solved in an integrated Excel-R-GAMS environment.

In the model, Canada is divided into five regions – Atlantic Canada, Central Canada, Alberta, BC Interior and BC Coast. The United States is divided into three regions (South, North, West), and Asia is separated into China, Japan and Rest of Asia. Chile, Australia, New Zealand, Finland, Sweden and Russia are also separate regions, while the remaining regions comprise Rest of Europe, Rest of Latin America, and the Rest of the World (ROW). The model calculates production of coniferous logs and wood products and their consumption in each region, and bilateral region-to-region trade flows of the wood products as outlined in Figure 2.2.

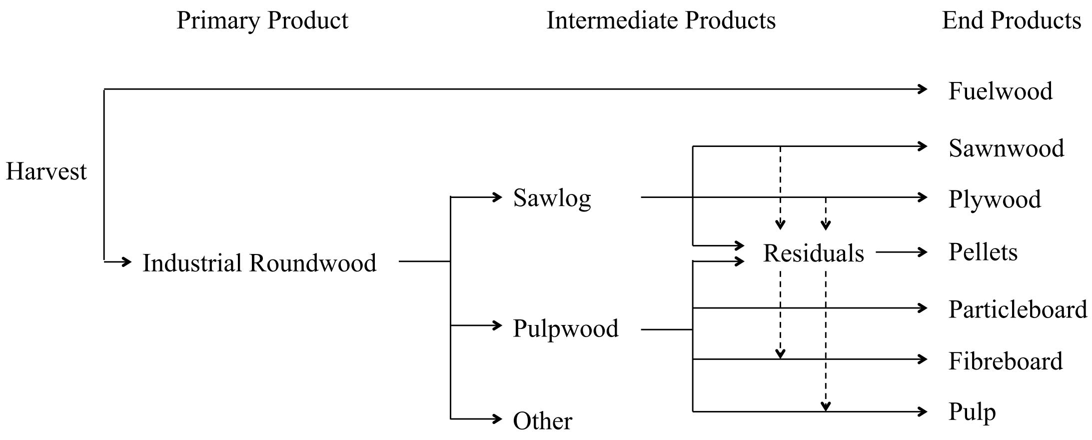

Figure 2.2: Forest Product Flow Chart

The initial supply of industrial roundwood provides the fibre for a number of downstream products: sawnwood (lumber), plywood, particleboard, fibreboard, pulp and wood pellets. The production of sawnwood and plywood coincide with the production of residuals in the form of chips and sawdust that can be used to produce fibreboard, pulp and wood pellets. The harvest and process of industrial roundwood from the initial harvest produces residuals (roadside debris; tree tops, branches, other debris), which may also be used in the production of wood pellets (although this is not done here). Finally, industrial roundwood may be diverted to fuelwood (as indicated by the dashed line in Figure 2.2).

Each region is assumed to have a set of linear (inverse) demand and supply curves for each downstream product *k* (defined earlier):

$$P_d^k = \alpha_d^k - \beta_d^k q_d^k , \qquad (2.3)$$

$$P_s^k = a_s^k + b_s^k q_s^k \ , \tag{2.4}$$

where d (=1, …, D) and s (=1, …, S) refer to demand and supply regions, respectively.

The objective of the forest trade model is to maximize the sum of the consumer surpluses and producer surpluses across all relevant markets. As previously mentioned, the demand for logs is derived from the demand for downstream products, so the consumer surplus in the log market is evaluated as the sum of the changes in producer surpluses in the downstream vertical markets. For downstream products that use logs as inputs in production, the consumer and producer surpluses are found by maximizing the sum of the areas under the D demand schedules (2.3) and subtracting the sum of the areas under the S supply schedules (2.4). These respective areas are given by:

$$B_d^k = \int_0^{q_d^k} (\alpha_d^k - \beta_d^k x)\,dx = \alpha_d^k q_d^k - \frac{1}{2}\beta_d^k q_d^{k^2} \ , \tag{2.5}$$

$$C_s^k = \int_0^{q_s^k} (a_s^k + b_x^k x)\,dx = a_s^k q_s^k + \frac{1}{2} b_s^k q_s^{k^2} \ , \tag{2.6}$$

where x is an integration variable, B_d^k is the total benefit (area under demand) in demand region d for product k, and C_s^k is the total cost (area under supply) in supply region s for product k.

In the market for industrial roundwood, the area above the price and below the demand curve is another measure for the sum of the producer surpluses found in the downstream markets, and thus does not need be counted. However, the producer surplus to the log producers needs to be included. Assume the supply, or marginal cost, of logs in log producing region j is linear: $r_j = m_j + n_j Q_j$, where Q_j is the quantity of logs in country j. Thus, the producer surplus from logs from any region j is given by:

$$R_j = r_j Q_j - \int_0^{Q_j} (m_j + n_j x)\,dx = \frac{1}{2} n_j Q_j^2 \ . \tag{2.7}$$

Computation of the spatial price equilibrium model involves the sum of the necessary producer and consumer surpluses as outlined above, while subtracting transportation costs and associated taxes. Then the objective function to be maximized can be written as:

$$W = \sum_{d=1}^{D}\sum_{k=1}^{K} B_d^k - \sum_{s=1}^{S}\sum_{k=1}^{K} C_s^k + \sum_{j=1}^{J} R_j - \sum_{j=1}^{J}\sum_{s=1}^{S}\left(\delta T_{js} + t_{js}\right) Q_{js} - \sum_{s=1}^{S}\sum_{d=1}^{D}\sum_{k=1}^{K}\left(T_{sd}^k + t_{sd}^k\right) q_{sd}^k , \tag{2.8}$$

where W refers to the overall wellbeing brought about through the global forest products industry, T is the cost (\$/m^3) of transporting forest products from supply region s to demand region d for the case of k downstream products, and from log producing region j to log consuming region s for the case of industrial roundwood. The separation is important, as δ is a parameter that takes into account the extra cost of transporting logs because they occupy more space per cubic meter than other wood products. Finally, t_{js} is the tax on logs (\$/m^3) originating in log supply region j and sold to wood product producing region s, while t_{sd}^k is the tax on wood product k originating in supply region s, destined for demand region d.

Objective (2.8) is maximized subject to a series of biophysical and economic constraints relating to the availability of timber harvests, log supply, and wood product manufacturing limits (see Appendix). The essential constraints are material flow and productivity constraints that ensure the total supply equals total demand for each country and each product.

The method used to calibrate the global trade model relies on positive mathematical programming (PMP) developed by Howitt (1995) and, in the case of spatial modelling, by Paris et al. (2011). For a detailed description of the particular application of PMP to the international trade of forest products see van Kooten and Johnston (2014), although the current model is calibrated for 2011 rather than 2010. Data come primarily from the Food and Agricultural Organization of the United Nations (FAO, 2013), with supplementary information from the Government of Canada (2012), BC Statistics (2013), Random Lengths (various years), the University of Washington's Center for International Trade in Forest Products (CINTRAFOR), and the Global Forest Products Model (GFPM) at the University of Wisconsin (see Buongiorno et al., 2003). For a more detailed description of the data, refer to the Appendix.

2.2.3 Scenario Description

To assess the impact of increased global demand for wood pellets on the rest of the forest product industry, we consider a scenario where demand is doubled. To simulate such an increase in the demand for wood pellets, we assume a vertical increase in the demand curve for pellets in each region, which implies adjusting the demand intercept α_d^{pellet}. The significant producers of wood pellets during 2011 are provided in Table 2.1.

The forest spatial price equilibrium trade model for coniferous forest products was used to evaluate the effects of increased global wood pellet demand in each country, and the corresponding change in production, consumption and trade flows were endogenously determined. The model allows fibre inputs of industrial roundwood, chips and residuals to be used in the production of forest products, where increased competition for inputs will inevitably impact the remaining forest product industry.

Table 2.1: Production and capacity for select wood pellet producing regions, 2011

Region	Pellet production ('000 tonnes)	Proportion of sawlogs + veneer logs coniferous (%)	Coniferous pellet production ('000 tonnes)[a]	Total pellet production capacity (tonnes/yr)
Alberta	82	93	76	145
Atlantic Canada	278	85	237	493
BC Interior	1,259	95	1,196	1,875
Rest of Canada	417	85	355	739
China	600	64	384	750
Russia	1,612	78	1,265	3,100
Sweden	1,340	99	1,332	2,500
US North	1,125	79	894	3,410
US South	1,355	79	1,076	3,500
US West	310	79	246	940
Rest of Europe	7,806	82	6,365	14,146
Rest of World	423	81	344	603
TOTAL	16,607		13,769	32,201

Sources: USDA (2013), CFS (2014), Lamers et al., (2012)

[a] Proportion of coniferous sawlogs + veneer logs multiplied by total wood pellet production

2.3 Results

Increasing the demand for wood pellets increases the derived demand for logs, resulting in higher prices as well as increased global production. The price of industrial roundwood is projected to increase by 1.1 percent globally, while the quantity demanded within a given region varies. For example, the quantity of industrial roundwood demanded in Canada is projected to increase by 1.4 percent as a result of doubling global wood pellet demand, while it is projected to increase by 1.7 percent in Europe.

The impact of increased wood pellet demand on the lumber and plywood markets was indeterminate and could only be determined numerically. The projected impact of doubling global wood pellet demand on the international lumber and plywood markets is presented in Table 2.2. Results suggest that increased wood pellet demand is beneficial to these markets, as the residuals associated with lumber and plywood production become more valuable. In the lumber market, regional prices decline by 5.0 to 7.1 percent, while the quantities demanded and supplied increase in all regions. It is clear that consumers of lumber are made better off through increased consumption and reduced prices, while it remains unclear how producers of lumber will ultimately be affected as a result of increased production and lower selling prices.

Table 2.2: Projected change in global sawnwood and plywood markets

	Change from base case (%):					
	Lumber			Plywood		
Region	P^d	Q^d	Q^s	P^d	Q^d	Q^s
Canada	-7.08	1.17	1.40	-0.96	0.58	1.39
US	-4.98	0.84	0.54	-0.81	0.48	0.65
Russia	-7.08	1.20	1.93	-1.14	0.67	1.04
Europe	-6.14	1.29	2.34	-0.72	0.35	1.26
ROW	-6.40	1.32	0.48	-0.89	0.51	0.53

The impact of increased wood pellet demand has a similar impact on the plywood market, yet the magnitudes of the changes are smaller compared to the lumber market. The fraction of residuals (i.e., chips and sawdust) associated with plywood and veneer production is lower compared to lumber, resulting in a smaller impact in the plywood market when these residuals increase in value. Further, some of the by-products associated with veneer production have greater value when used in other markets (e.g., peeler cores). Nonetheless, increased wood pellet demand will positively impact consumers of plywood (Table 2.2), while again it is unclear how producers will be affected through increased production, but lower selling prices.

A significant increase in global wood pellet demand may be detrimental to products that compete for fibre with wood pellets, as shown in Table 2.3. The particleboard market utilizes chips, flakes, splinters and strands derived primarily from processing pulpwood. Direct completion for these residuals comes from wood pulp producers, as well in extreme cases with dedicated harvests of logs for energy. Wood pellets compete directly for residual fibre and pulp logs with traditional users such as particleboard and pulp. According to Table 2.3, doubling global demand for wood pellets will result in an increase in regional particleboard prices from 9.2 to 19.5 percent, with consumption and production falling from 2.8 to as much as 8.5 percent. Consumers are adversely impacted by this change as they now consume less because prices have increased. On the other hand, producers benefit from increased prices, but ultimately manufacture less particleboard.

Table 2.3: Projected change in global particleboard, fibreboard and wood pulp markets

	Change from base case (%):								
	Particleboard			Fibreboard			Wood pulp		
Region	P^d	Q^d	Q^s	P^d	Q^d	Q^s	P^d	Q^d	Q^s
Canada	18.20	-7.97	-7.73	7.66	-5.40	-7.62	11.11	-4.06	-7.46
US	9.24	-4.14	-2.95	10.73	-7.80	-4.64	12.15	-4.12	-3.90
Russia	19.54	-8.46	-3.47	7.72	-5.45	-5.15	12.44	-4.19	-4.68
Europe	11.26	-4.97	-8.46	4.16	-4.09	-8.50	10.18	-3.40	-3.80
ROW	12.88	-5.52	-2.76	7.80	-6.06	-5.67	12.20	-4.46	-3.10

Unlike particleboard manufacturing, fibreboard uses purchased wood residuals that are flat pressed to produce panels. These residuals are often sourced from sawmills and are an input used in wood pellet manufacturing. Clearly, increasing wood pellet demand will create additional competition for these wood residues, which traditionally have been relied upon for producing fibreboard. Doubling wood pellet demand will result in an increase in the price of fibreboard anywhere between 4.2 and 10.7 percent (Table 2.3). Consumption of fibreboard falls by approximately 4.1 to 8.5 percent. The combination of a price rise and reduced consumption leads to consumers being worse off. Again, it is unclear what effect increased wood pellet demand will ultimately have on producers of fibreboard as prices rise and production falls in all regions.

Finally, wood pellets will compete for fibre with the wood pulp industry that relies on pulpwood, wood chips and residues to be converted into pulp either mechanically or chemically. In Table 2.3, doubling global wood pellet demand is projected to raise the price of wood pulp by 10.2 to 12.4 percent, while production and consumption declines across all regions. Consistent with the markets for particleboard and fibreboard, consumers lose through the rise in prices and reduced consumption, while it is again unclear how producers will be affected.

Although there are exceptions (salvage harvesting mountain pine beetle damaged timber in Canada), the wood pellet sector has traditionally utilized low-cost mill residuals as feedstock, but significant increases in production will require incorporation of more costly fibre from forest operations. This simulation shows that the wood pellet industry draws fibre away from traditional forest products. As indicated in Table 2.4, an increase in wood pellet demand will substantially increase the price of wood pellets by 111.1 to 157.5 percent. Thus, retrofitted power plants that co-fire pellets with coal will ultimately experience a dramatic increase in the price of fuel as future demand for wood pellets grows, while pellet supplying regions (primarily Canada, the U.S., Russia and Europe) will greatly benefit.

Table 2.4: Projected change in global wood pellet markets

	Change from base case (%):		
Region	P^d	Q^d	Q^s
Canada	157.48	54.35	140.63
US	141.88	71.21	116.57
Russia	115.62	82.40	75.10
Europe	111.09	90.86	73.41
ROW	126.39	81.05	386.17

2.4 Summary and Discussion

In this chapter we assessed the impact of increased demand for wood pellets on the global forest products industry using a global wood products trade model developed the Appendix. The model integrates wood product markets vertically into upstream log markets and downstream markets for final commodities made from wood fibre, and horizontally across five types of wood products. Unlike other forest trade models, the model is calibrated to duplicate bi-lateral trade flows precisely (van Kooten and Johnston 2014).

From a bioenergy standpoint, one aspect of the research is the distinction between fuelwood and wood pellets. This is important for two reasons: First, fuelwood is used locally for subsistence living, while wood pellets are demanded globally for large-scale energy production (primarily in coal-fired plants). Second, as many countries have implemented aggressive renewable energy policies that require the use of wood pellets or their equivalent (e.g., torrefied wood pellets) to generate electricity, output of many other wood products is impacted, unlike with fuelwood. While some products are complements to wood pellets in production, namely sawnwood and plywood, others must compete with wood pellets for residual fibre (pulp, fibreboard, particleboard). This inevitably results in differing outcomes for these two product groups. Further, the demand for roundwood logs is impacted, thereby potentially influencing silvicultural decisions. For example, if agricultural prices and policies remain unchanged, it is possible that in the long run agricultural land is converted to plantation forests to produce wood pellets.

Our results indicate that, if wood pellet demand reduces the costs of processing logs, there will also be an increase in the output of these products (lumber, plywood) that leads to an increase in the price of logs. This cost reduction occurs because the joint-product, namely wood residuals, generates extra value in production of lumber and/or plywood. Not only would more logs be brought to market as their price is higher (thus incentivizing a shift in land use towards forestry), but lumber and plywood output would increase benefitting consumers. On the other hand, the output of fibreboard, particleboard and pulp will decline because these products must compete with wood pellets for residual fibre, the price of which has gone up. The consumers of these products will suffer a loss in welfare.

Because wood pellet prices increase in all regions as a result of incentives or mandates to co-fire pellets with coal in power plants, there are unintended consequences. Some of these were discussed in the preceding paragraphs. But there is a more serious problem: Will wood pellet prices rise to a point where wood biomass is no longer an economical renewable source of energy? Many regions around the world have embarked on policies intended to reduce their CO_2 emissions by relying more on bioenergy to meet aggressive renewable energy targets. For example, the EU has mandated renewable energy targets to be achieved by the year 2030 (2030 Policy Framework for Climate and Energy), while many coal-fired power plants in the province of Ontario have been retrofitted to run off biomass in the near future (Ontario Green Energy Act). However, simultaneous implementation of such policies could well undermine this particular renewable energy strategy as wood pellet prices double or much more in our scenarios.

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Chapter 3

INCREASING EUROPE'S BIOENERGY DEMAND: WHO STANDS TO BENEFIT?

3.1 Introduction

In order to curb carbon dioxide (CO_2) emissions, governments within the European Union (EU) are increasingly turning to biomass to meet renewable energy targets. In particular, it is becoming popular to co-fire biomass (wood pellets) with coal to reduce the CO_2-emissions intensity of existing coal-plants.[6] As a result, installed biomass capacity within the EU has increased from 1.44 GW in 2004 to 34.37 GW in 2012, representing 43.3% of global biomass capacity. Forest biomass is expected to be the most significant future source of renewable energy within the EU, accounting for over half of the total renewable energy production (European Commission, 2013). Yet little is known about how increased demand for biomass in the EU will impact the rest of the global forest products industry. Timber rich regions will undoubtedly benefit from increased demand for wood fibre, but other wood product markets may experience significant changes in prices from increased competition for fibre.

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[6] Co-firing biomass in existing coal-fired power plants is appealing due to the low incremental investment required to retrofit established facilities and because energy produced from biomass is considered to be carbon neutral (IPCC 2006). Under Intergovernmental Panel on Climate Change (IPCC) reporting rules, the impacts of energy produced from biomass would not be reported in the energy sector but in the Agriculture, Forestry and Other Land-Use (AFOLU) sector, previously known as the Land Use, Land-Use Change and Forestry (LULUCF). Carbon emissions from biomass energy are considered carbon neutral since the IPCC Guidelines assume that carbon lost during harvest equals carbon gained through re-growth, so there are no net CO_2 contributions (see van Kooten and Johnston, 2014).

Given the enormous amount of fibre that is expected to be demanded by the EU, it is necessary to examine the economic impact of renewable energy policies in an international context. The import of wood pellets into the EU has risen to 8.3 million tonnes (Mt) in 2012 from an insignificant amount a decade earlier (FAO, 2012). Indeed, the forest products industry as a whole has emerged as an interconnected global market, because the business model is based upon capturing comparative advantages wherever they lie. As a result, a country's domestic forest product sector is inevitably linked to international markets. Global trade in forest products was US$ 231 billion in 2012, which is an inflation adjusted increase of US$ 69.8 billion over the previous decade.[7] Thus, any assessment of increased EU bioenergy demand must be viewed in the context of international markets.

Not only is the forest products industry connected through international trade, it is also comprised of many interconnected wood products. As wood fibre is generally sourced from the initial harvest of logs, the manufacturing of secondary wood products will not only be affected by the supply of logs, but also by competition for residual fibre. In fact, the initial demand for logs is derived from the demands for various manufactured wood products. Any structural shifts in the market for one of these products will inevitably impact the others.

Studies looking at the regional effects of greater reliance on bioenergy find that a significant increase in bioenergy demand could see fibre redirected away from traditional timber products and rapid expansion of forest area (Ince et al., 2011, 2012; Moiseyev et al., 2011). However, such a narrow scope lacks a detailed description of the global forestry sector and thus fails to consider the interactions between fibre for bioenergy purposes and other forest products (see Ranseses et al., 1998; Fischer and Schrattenholzer, 2001; Yamamoto et al., 2000, 2001; Sands and Leimbach, 2003; Gillingham et al., 2008; Popp et al., 2011). Favero and Mendelsohn (2013) address this shortcoming by integrating a detailed global dynamic model of the forest sector, the Global Timber Model (GTM) of (Sohngen et al., 1999), with the WITCH model of climate and energy (Bosetti et al., 2009). Since their focus is only the U.S., they do not attempt to identify distinct country-to-country trade flows.

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[7] This figure represents the export value among all 159 countries represented in the FAOSTAT database across all forest products. Values are adjusted using the U.S. annual CPI index from the U.S. Bureau of Labor Statistics.

Few studies have assessed the implications of increased bioenergy demand on the global forest products sector. Using the Global Forest Products Model (GFPM) (Buongiorno et al., 2003), studies have examined roundwood used as a fuel for cooking, heating and/or production of electricity; that is, studies have focused on a broad category of fuelwood. For example, Raunikar et al. (2010) modified the GFPM to consider the impacts of increased fuelwood for bioenergy and the implications for other wood products for two IPCC scenarios, A1B and A2.[8] The authors found that the prices of fuelwood and industrial roundwood converged, while the prices of other forest products, including sawnwood, panels and pulp, rose significantly. Subsequently, Buongiorno et al. (2011) compared a high global bioenergy growth scenario (doubling demand for fuelwood by 2030) relative to a low scenario (20% increase). Although the projected effects varied from country-to-country, the authors also found that an increase in the global demand for fuelwood would lead to a rise in the prices of all wood products. The major shortcoming with these studies relates to the use of the fuelwood category at the global level – the great majority of fuelwood is used regionally for subsistence living, providing fuel for space heating and cooking.[9] In contrast, the recent rise in bioenergy demand, particularly in the EU, is driven by the need for biomass for electricity, which is met primarily by residuals from wood product manufacturing and is processed into wood pellets. If this is the case, increased bioenergy demand will not necessarily increase the prices of all wood products (see Chapter 2), as found in the previous studies. Unlike fuelwood, wood pellet manufacturing is interconnected with the production of other primary wood products in an intricate manner.

Chapter 2 showed that increased bioenergy demand (via wood pellets) results in the re-direction of residual fibre away from traditional wood product markets (viz., particleboard, fibreboard, pulp) and toward wood pellets. Wood pellets in this case are competitive in production with particleboard and other products that employ residual fibre from lumber and plywood manufacture. Thus, an increase in the demand for bioenergy increases the price of wood

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[8] Scenario A1B assumes continued globalization and high-income growth as compared to scenario A2 that assumes the opposite.

[9] FAO, Energy for Subsistence. At: http://www.fao.org/docrep/q4960e/q4960e03.htm (Accessed 23 January 2014)

residuals. Because producers of lumber and plywood are able to sell wood residuals at a higher price, this effectively increases the value of the marginal product of the sawmilling sector (or lowers the cost of producing the primary output from that sector). This in turn increases the supply of sawn- and ply-wood and the supply of the complementary product, wood residuals. It is the extent to which the two effects offset one another that determines the eventual impact on prices, and this will vary from one region to another and across different forest products.

This chapter focuses on the rapid expansion in bioenergy demand in the EU, and its impact on the global forest products industry. In sub-section 3.1.1, we provide a detailed discussion of the relevant bioenergy policies and market trends in the EU, followed in section 3.2 by a description of the global forest products trade model employed in this application. The results are provided in section 3.3, and these indicate the impact of the proposed rapid expansion of bioenergy needs in the EU on global prices, consumption and production of various wood products in various regions, and the accompanying changes in regional and global welfares. The conclusions and implications ensue.

3.1.1 Bioenergy in the EU

Although energy is produced in many regions by burning biomass, the European Union currently accounts for approximately 43% of globally installed bioenergy capacity. This heavy reliance on biomass for energy production is a result of aggressive EU policies as member states agreed to attain three targets by 2020 – a minimum 20% CO_2-emissions reduction from 1990 levels, a minimum 20% share of renewables in energy production, and a 20% improvement in energy efficiency. These are collectively referred to as the EU's "20-20-20" target. Country-specific, binding renewable energy targets have been developed to meet this target by 2020 as indicated in Figure 3.1.

Depending on a country's resource endowment, the binding target may be more or less than the EU-27's overall target.[10] For example, Malta is obligated to produce a minimum of 10%

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[10] Article 4 of Directive 2009/28/EC on Renewable Energy requires EU member states to submit national renewable energy Actions Plans to provide a roadmap for how each member state expects to reach its legally binding 2020 target for their share of renewable energy in their final energy consumption.

of its total energy from renewable sources by 2020, compared to Sweden's mandatory target of 49%. The European Commission (2013) estimates that meeting the 20-20-20 target could result in an annual wood deficit for Europe of 200 to 260 million m^3 by 2020. For comparison, Canada is a major producer and exporter of wood products, but it only harvests about 200 million m^3 of fibre per year.

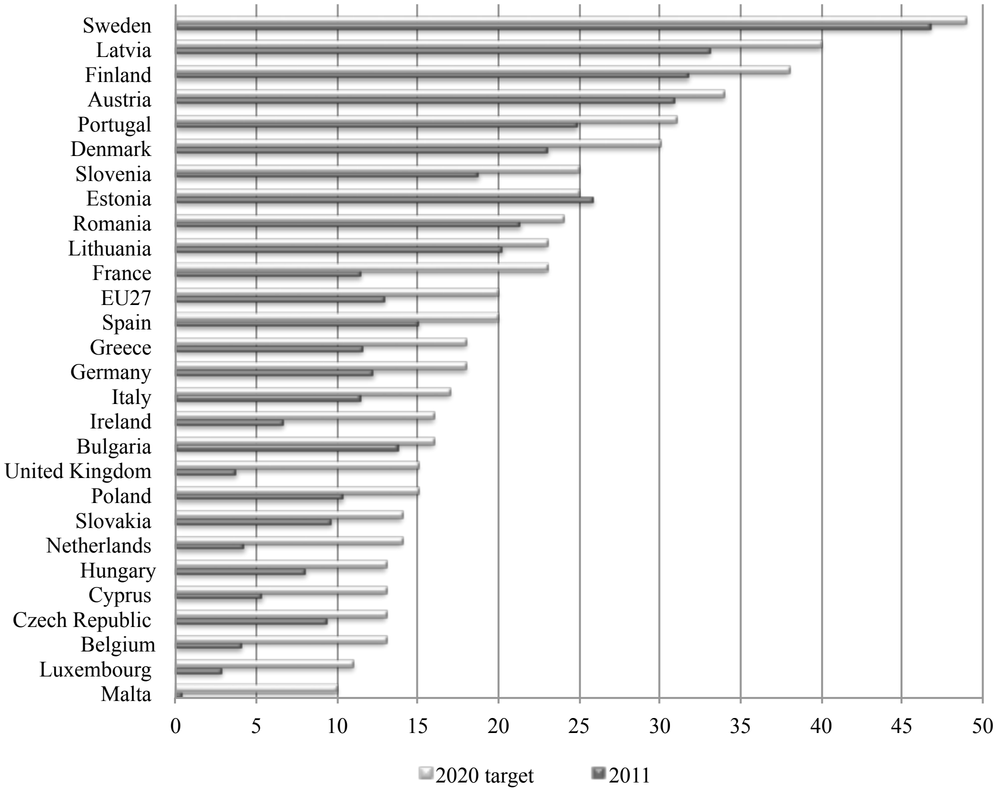

Figure 3.1: Share of renewable energy from total energy production in EU-27, 2011 (%)
Source: Eurostat (accessed 02.22.2014)

In early 2014, the European Commission (2014) proposed a new policy framework that abandons country-specific targets for a more ambitious greenhouse gas reduction target of 40% of 1990 levels by 2030, with renewable energy to account for 27% of the EU's total energy production by then. Although this new framework provides greater flexibility for a given country to reduce its emissions, the EU expects countries to build upon the 20-20-20 target to pursue the new EU target of 27% by 2030.

Table 3.1: Select Government Support for Biomass Electricity Generation in the EU

Country	Policy	Detail
Austria	Feed-in tariff (ÖSG 2012)	According to maximum capacity: If application submitted before 2013: €110 – 200/MWh; If application submitted during 2013: €109.4 - 200/MWh; If capacity exceeds 100 MW: €89 - 140/MWh
Belgium	Quota system	Electricity suppliers must prove, by submitting certificates, that a certain statutory and continuously increasing proportion (quota) of the electricity they supply was generated from renewable sources. Permit values were €81-95.23MWh in 2013.
Bulgaria	Feed-in tariff (Energy from Renewable Sources Act)	Wood waste: €114-128MWh.
Croatia	Feed-in tariff (Art. 28 Energy Act)	≤ 300 KW: €170/MWh > 300 KW and ≤ 2 MW: €158/MWh > 2 MW and ≤ 5 MW: €151/MWh > 5 MW and ≤ 10 MW: €138/MWh > 10 MW: €118/MWh
Cyprus	Premium tariff (SSRES)	Purchase price and variable top-up to cover the difference between the purchase price and guaranteed tariff. €135/MWh (market price of €117.9 + premium of €17.1 for the use of dry anaerobic digestion technology and CHP plants)
Czech Republic	Feed-in tariff Or Green Bonus	Feed-in tariff only for plants ≤ 100 KW: €80-144/MWh Green Bonus: electricity generated is supported through bonus payments equal to €39-103/MWh (technology specific)
Denmark	Premium tariff (Law on the Promotion of Renewable Energy)	Plant operators receive a variable bonus on top of the market price to a maximum of €110/MWh. Co-firing: €60/MWh. Other: no less than : €20/MWh.
Estonia	Premium tariff (§ 59 par. 1, 2 ELTS)	The operators of renewable energy systems may sell the electricity produced on the market to receive €53.7/MWh. If below 10MW, tariff amounts to €32/MWh.
Finland	Premium tariff	The premium, paid on top of the market price, is variable and depends on the electricity market price. Target is €83.5/MWh.
France	Feed-in tariff	€43.4/MWh plus a premium of at least €77.1/MWh depending on energy efficiency, system capacity and input.
Germany	Feed-in tariff (EEG + BiomasseV)	€143/MWh depending on plant size plus, if applicable, a bonus of €25-80/MWh for use of special substances.
Greece	Feed-in tariff (Law No. 3468/2006)	≤ 1 MW: €200/MWh > 1 MW and ≤ 5 MW: €175/MWh > 5 MW: €150/MWh
Hungary	Feed-in tariff (§ 11 (3) Act No. LXXXVI of 2007)	Varies depending on peak, mid-peak, or off-peak time: < 20 MW: €42.41-116.15/MWh > 20 MW and < 50 MW: €33.92-92.89/MWh > 50 MW: €46.22-72.22/MWh

Iceland	Feed-in tariff (REFIT)	CHP from biomass ≤ 1.5 MW: €146/MWh CHP from biomass > 1.5 MW: €125/MWh General biomass combustion of all sizes gets €89/MWh
Italy	Feed-in tariff II (Art. 7 AEEG 280/07)	For outputs up to 2 GWh: €113/MWh For outputs above 2 GWh: Market price
Latvia	Feed-in tariff (Electricity Market Law; No. 2 Reg. No. 262)	The feed-tariff is currently on hold until 01.01.2016.
Luxembourg	Feed-in tariff	≤ 1 MW: €145/MWh > 1 MW and ≤ 5 MW: €125/MWh
Netherlands	SDE+ premium feed-in scheme	≤ 10 MW; €70-147/MWh > 10 MW and ≤ 100 MW; €70-78.28/MWh Extension of operating period; €67.32/MWh
Norway	Quota + certificates (Electricity Certificates Act)	Electricity suppliers must prove that a certain quota supplied was generated from renewable sources. Proof is provided by means of tradable certificates. Traded on open market
Poland	Quota (Green Certificate)	Electricity suppliers must prove that a certain quota supplied was generated from renewable sources. Proof is provided by means of tradable certificates. €45/MWh (Early 2013)
Portugal	Feed-in tariff	Indicative average rate: €119/MWh (DL 5/2011)
Romania	Quota (Green Certificate)	Electricity suppliers must prove that a certain quota supplied was generated from renewable sources. Proof is provided by means of tradable certificates. Traded on open market
Slovakia	Feed-in tariff	2013: €112.24/MWh 2014: €92.09/MWh
Slovenia	Premium + Feed-in tariff	Biomass must be at least 90% of input: €185.7/MWh
Sweden	Quota (Electricity Certificates Act)	Electricity suppliers must prove that a certain quota supplied was generated from renewable sources. Proof is provided by means of tradable certificates. €20.26/MWh (2012-2013 avg).
Switzerland	Feed-in tariff (art. 1 c of the Energy Act (EnG))	Tariffs are composed of a base payment + bonuses: ≤ 50 KW: €230/MWh + €67/MWh ≤ 100 KW: €208/MWh + €58/MWh ≤ 500 KW: €183/MWh + €50/MWh ≤ 5 MW: €154/MWh + €33/MWh > 5MW: €146/MWh + €29/MWh
United Kingdom	Renewable Obligation Certificate (ROC)	Applicable to plants > 5MW. Requires ROC's to cover quota obligations; ROC's allocated and traded in regards to quota. €55.9/MWh (2012)

Source: European Commission Legal Sources on Renewable Energy (RES – LEGAL).

Without exception, every country within the EU has implemented policies promoting the use of biomass in energy generation. An overview of individual country policies that promote the use of renewable energy, especially biomass sources, is found in Table 3.1. Many of the policies fall within three main categories: (1) feed-in tariffs for electricity, (2) direct subsidies paid over and above market price up to a maximum threshold price, and/or (3) a quota with a transferable permit component that can be traded on the open market.

Policies promoting bioenergy production have resulted in Europe becoming one of the most bioenergy intensive regions in the world. As of 2012, EU-27 countries had a reported 32.82 GW of installed biomass electrical-generating capacity (see Table 3.2). Although bioenergy includes the combustion of wood, wood waste, straw, corn stover, manure and other bio-materials, co-firing wood pellets in retrofitted coal plants is becoming the most significant form of bioenergy, which has resulted in increasing international trade flows (IEEP, 2010).

Wood pellet consumption within the European Union is projected to rise by varying degrees over the coming decade, from 13.6 Mt in 2012 to as much as 35.0 Mt in 2020 (Pöyry, 2011). The EU's National Renewable Energy Action Plan (NREAP, 2011) projects bioenergy to more than double from 5.4% of final energy consumption to 12.0% by 2020, with wood pellets continuing to be the major source of bioenergy in the future, contributing to 36% of the 2020 target. Mantau et al. (2010), for example, argue that biomass consumption for energy generation within Europe will grow by more than 227 million m^3 in a decade – from 346 million m^3 in 2010 to 573 million m^3 in 2020. However, the new 2030 framework released early in 2014 (European Commission 2014) provides an even more ambitious target: 27% of all energy produced in the EU is to come from renewable sources by 2030, compared to only 12% for 2020 in the 20-20-20 target. In that case, Mantau et al. (2010) suggest that biomass consumption for energy generation within Europe may grow to 752 million m^3 by 2030, or by 4% per year between 2010 and 2030.

Perhaps not surprising, there is no consensus on exactly how much biomass Europe will demand by the end of the target period. In 2012, consumption of wood pellets in EU-27 countries totalled 13.6 Mt, with Denmark, Germany, Italy, Sweden and the United Kingdom leading the way (Table 3.2). While there is significant pellet production capacity within the EU-27, member states imported 8.4 Mt of wood pellets in 2012, with 4.3 Mt coming from outside the EU. The most significant importers of wood pellets were Denmark and the United Kingdom, importing 2.0 and 1.5 Mt of wood pellets, respectively (Table 3.2).

Table 3.2: Installed biomass capacity, consumption and import of wood pellets, EU-27, 2012

	Installed Capacity (GW)[a]	Wood Pellets	
		Apparent consumption (kt)[b,c]	Imports (ktonnes)[b]
Austria	4.49	688.86	272.14
Belgium	1.29	933.89	972.32
Bulgaria	0.01	104.49	22.26
Cyprus	0.00	0.00	0.00
Czech Republic	0.53	45.56	25.48
Denmark	1.22	2,048.95	2,000.24
Estonia	0.07	84.25	14.67
Finland	1.91	219.09	28.27
France	1.47	604.28	25.55
Germany	7.11	1,813.00	347.47
Greece	0.09	52.92	17.92
Hungary	0.52	12.82	9.79
Ireland	0.04	23.41	24.12
Italy	2.86	1,492.00	1,197.00
Latvia	0.01	110.99	34.02
Lithuania	0.03	21.78	39.57
Luxembourg	0.03	6.00	2.41
Malta	0.00	0.15	0.15
Netherlands	1.60	880.26	1,042.66
Poland	0.23	684.93	194.59
Portugal	0.60	154.29	23.81
Romania	0.02	65.20	0.84
Slovakia	0.20	53.84	6.61
Slovenia	0.05	100.40	60.17
Spain	1.01	230.95	16.32
Sweden	4.21	1,488.82	488.16
United Kingdom	3.26	1,711.29	1,486.88
EU-27	**32.82**	**13,632.43**	**8,353.42**

[a] Source: EIA (2014)
[b] Source: FAO (2012)
[c] Apparent consumption = Production + Imports – Exports

Although intra-EU trade in wood pellets is an important component of the international market, the United States, Canada and Russia represent significant sources of pellets from outside the EU (see Figure 3.2). In 2012, these three countries exported 3.8 Mt of wood pellets to the EU, and are expected to remain significant trade partners as European bioenergy expands in the future. Imports of wood pellets from outside EU member states will likely play a significant role as the EU strives towards meeting its renewable energy targets in the next decade and beyond. Wood pellet imports from non-EU countries are forecast to increase from 4.3 Mt in 2012 to 16.0 Mt by 2020 (IEA Bioenergy Task 40, 2011). Imports from timber rich regions such as the United States, Canada and Russia are projected to continue, although this will have consequences for the global forest products sector.

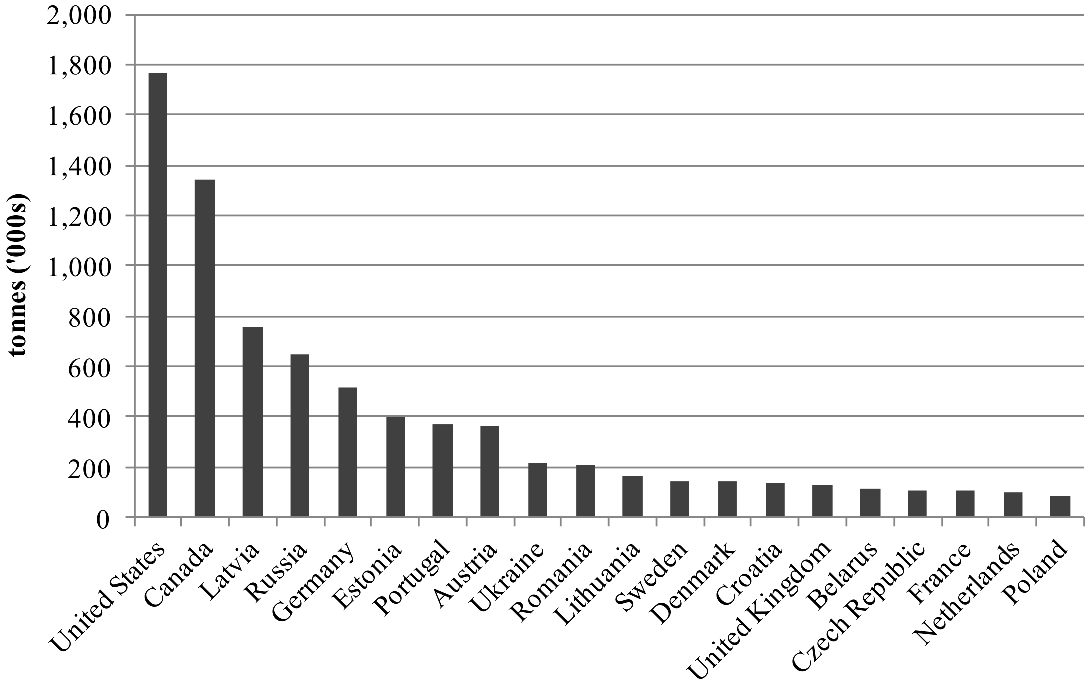

Figure 3.2: Top twenty origins of wood pellet shipments to EU-27 countries, 2012.
Source: Eurostat (accessed 06.01.2014)

While there remains uncertainty about the impact that the EU's binding renewable energy targets will have on the growth in wood pellet consumption within Europe, the purpose of this chapter is not to forecast potential wood pellet requirements in the EU, but rather to investigate the impact that a substantial increase in wood pellet demand will have on the global forest products sector. Therefore, a 20-region, integrated global forest sector trade model is described and used to estimate the economic consequences of a simple doubling of current wood pellet consumption in Europe.

3.2 Methods

The modelling framework employed in this chapter follows the forest sector as depicted in Figure 3.3. The initial harvest can be broken down into two parts: first, the supply of industrial roundwood provides fibre for a number of downstream products, such as sawnwood (lumber), plywood, particleboard, fibreboard, pulp and wood pellets; then, the supply of residuals for producing wood pellets (and other biomass for energy) derives directly from the initial harvest and indirectly as residuals (chips, sawdust) from the processing of industrial roundwood logs into lumber and plywood. However, both supplies of such fibre can be used to produce oriented strand board, fibreboard and pulp in addition to bioenergy products such as wood pellets. Finally, harvest residuals, such as tree tops, branches and other roadside debris, could also be used for energy purposes, including the production of wood pellets.

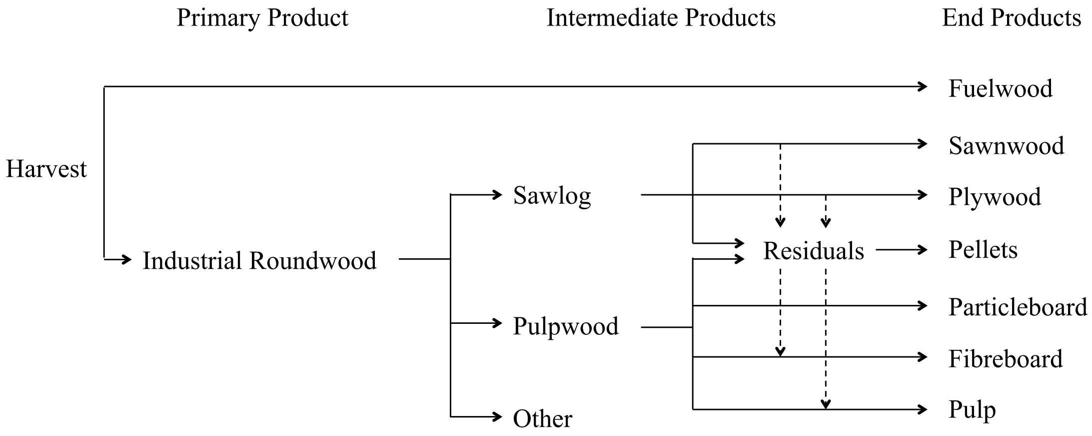

Figure 3.3: Forest Product Flow Chart

A global trade model for coniferous forest products based on the fibre flows indicated in Figure 3.3 is described in this section.[11] Following the law of one price, the spatial price equilibrium (SPE) trade model maximizes economic welfare for all products in all countries,

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[11] A detailed description of the multi-product global trade model and the data used in the current application can be found in Johnston and van Kooten (2014b). In an early application (refer to Chapter 2) an equi-proportional increase in the demand for wood bioenergy is assumed in every region. An earlier version of the model that considers only log-lumber trade investigated the impacts of the Russian log export ban and the U.S.-Canada lumber dispute (van Kooten and Johnston 2014).

assuming that differences in prices between regions are the result of shipping and handling costs (and including tariffs and other non-tariff barriers). The model calculates the production and consumption of coniferous logs and wood products in each region. The initial supply of industrial roundwood provides fibre for downstream products as described in Figure 3.3. First, harvest operations produce residuals primarily in the form of roadside debris that could be used to produce wood pellets, although this is not done here because of potentially high costs (Niquidet et al., 2012). However, the production of sawnwood and plywood provides residuals chips and sawdust that can be used to produce fibreboard, pulp and wood pellets. Further, some harvested logs may be diverted directly to bioenergy for a variety of reasons related primarily to their unsuitability in production of lumber or pulp (see top line in Figure 3.3).

Each region is assumed to have a set of linear (inverse) demand and supply schedules for each downstream product $k \in \{$lumber, plywood, particleboard, fibreboard, pulp, pellets$\}$:

$$P_d^k = \alpha_d^k - \beta_d^k q_d^k , \tag{3.1}$$

$$P_s^k = a_s^k + b_s^k q_s^k , \tag{3.2}$$

where d (=1, …, D) and s (=1, …, S) refer to demand and supply regions, respectively. The objective of the forest trade model is to maximize the sum of the consumer plus producer surpluses across all relevant markets. As previously mentioned, the demand for logs is derived from the demand for downstream products, so the consumer surplus in the log market is evaluated as the sum of the changes in producer surpluses in the immediately downstream markets. For downstream products that use logs as inputs in production, the consumer and producer surpluses are found by maximizing the sum of the areas under the D demand schedules (3.1) and subtracting the sum of the areas under the S supply schedules (3.2). These respective areas are given by:

$$B_d^k = \int_0^{q_d^k} (\alpha_d^k - \beta_d^k x)\, dx = \alpha_d^k q_d^k - \frac{1}{2} \beta_d^k q_d^{k^2} , \tag{3.3}$$

$$C_s^k = \int_0^{q_s^k} (a_s^k + b_x^k x)\, dx = a_s^k q_s^k + \frac{1}{2} b_s^k q_s^{k^2} , \tag{3.4}$$

where x is an integration variable, B_d^k is the total benefit (area under demand) in demand region d for product k, and C_s^k is the total cost (area under supply) in supply region s for product k.

In the market for industrial roundwood, the area above the price and below the demand curve is another measure for the sum of the producer surpluses found in the downstream markets, and thus does not need be counted. However, the producer surplus accruing to log producers needs to be included. Assume the supply (i.e., marginal cost) of logs in log producing region j is linear: $r_j = m_j + n_jQ_j$, where Q_j is the quantity of logs in j. Thus, the producer surplus from supply logs from any region j is given by:

$$R_j = r_jQ_j - \int_0^{Q_j} (m_j + n_jx)\,dx = \frac{1}{2}n_jQ_j^2 \,. \tag{3.5}$$

Computation of the spatial price equilibrium model involves the sum of the areas under the demand functions minus the relevant areas under the supply functions and minus shipping and handling costs (and relevant export taxes and import duties). Then the objective function to be maximized can be written as:

$$W = \sum_{k=1}^{K}\left(\sum_{d=1}^{D} B_d^k - \sum_{s=1}^{S} C_s^k - \sum_{s=1}^{S}\sum_{d=1}^{D}\left(T_{s,d}^k + \tau_{s,d}^k\right)q_{s,d}^k\right) + \sum_{j=1}^{J}\left(R_j - \sum_{s=1}^{S}\left(\delta T_{j,s} + \tau_{j,s}\right)\right), \tag{3.6}$$

where W refers to overall wellbeing in the global forest products sector; $\tau_{s,d}^k$ is the tariff (\$/m^3) imposed on a unit of product k shipped from supply region s to demand region d; $T_{s,d}^k$ is the shipping and handling (transaction) cost (\$/m^3) of shipping a unit of product k from supply region s to demand region d; and $q_{s,d}^k$ is the related quantity of k shipped s to d. Meanwhile, $T_{j,s}$ is the cost (\$/m^3) of transporting logs from supply region j to demand region s; the separation is important as δ is a parameter that takes into account the extra cost of transporting logs because they occupy more space per cubic meter than other wood products. Finally, $\tau_{j,s}$ is the tax on logs (\$/m^3) originating in log supply region j and sold to wood product producing region s, while $\boldsymbol{\tau}_{s,d}^k$ is the tax on wood product k originating in supply region s, destined for demand region d.

Objective (3.6) is maximized subject to a series of biophysical and economic constraints relating to the availability of timber harvests, log supply and wood product manufacturing limits (see Appendix). The essential constraints are material flow and productivity constraints that ensure that total supply equals total demand for each region and product.

Following Paris et al. (2011), positive mathematical programming (PMP) is used to calibrate the model. The method is described for the case of international trade in forest products by van Kooten and Johnston (2014). Data come primarily from the Food and Agricultural Organization of the United Nations (FAO, 2013), with supplementary information from the Government of Canada (2012), BC Statistics (2013), Random Lengths (various years), the University of Washington's Center for International Trade in Forest Products (CINTRAFOR), and the Global Forest Products Model (GFPM) at the University of Wisconsin (see Buongiorno et al., 2003). Greater detail concerning the data is provided in the Appendix. The numerical trade model is solved in an integrated Excel-R-GAMS software environment. Then, to simulate an increase in the European demand for wood pellets, the demand for wood pellets in the EU is assumed to double.[12] The effects of increased EU wood pellet demand on prices, production, consumption, trade flows and welfare are then evaluated.

3.3 Results

In this section, we present the results from a doubling of current wood pellet use in the EU. The discussion examines the impacts on each of the various components of the global forest sector, beginning with industrial roundwoood (logs) and then each of the wood products. Changes in prices, production, consumption and welfare are provided by region.

With respect to the logging sub-sector, forest trade model results project the world price of industrial roundwood to increase by slightly more than \$1 per m^3 while output increases by some 9.2 million m^3, or 1% (Table 3.3). Aggregate economic wellbeing improves in most industrial roundwood markets, with only consumers of industrial roundwood in Alberta and the U.S. South negatively affected since additional logs are exported to regions with comparative advantages in processing. According to Table 3.3, the global roundwood market experiences a \$1.3 billion welfare gain as a result of increased EU wood pellet demand, with gains evenly

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[12] The demand intercept, α_d^{pellet} is simply shifted upwards.

distributed among producers and consumers of logs. The magnitude of region specific welfare changes is driven largely by a region's ability to recover industrial roundwood from harvests and convert logs into products.

Table 3.3: Change in industrial roundwood markets by selected countries/regions

	Change in:								
	Price		Consumption		Production		Economic Welfare (Mill $):		
	$/m^3$		m^3 ('000s)		m^3 ('000s)		CS	PS	TOTAL[a]
Asia									
China	1.06	1%	221	0%	418	1%	16	33	50
Japan	1.16	1%	41	0%	160	1%	3	14	16
Rest of Asia	1.10	1%	61	1%	59	1%	4	4	8
Canada									
Alberta	0.99	1%	-171	-1%	145	1%	-15	12	-3
Atlantic Canada	1.08	1%	462	4%	102	1%	44	9	53
British Columbia Coast	1.05	1%	49	0%	135	1%	4	13	17
British Columbia Interior	0.86	1%	1,366	3%	522	1%	116	42	158
Rest of Canada	1.04	1%	624	2%	307	1%	61	29	89
Europe									
Finland	1.18	1%	216	1%	384	1%	8	25	33
Sweden	1.01	1%	301	0%	617	1%	11	41	52
Rest of Europe	0.92	1%	3,733	2%	1,782	1%	251	104	355
Oceania									
Australia	0.98	1%	33	0%	146	1%	0	9	8
New Zealand	0.98	1%	60	1%	116	1%	3	7	10
Russia	1.00	1%	780	1%	922	1%	54	67	121
South America									
Chile	0.98	1%	142	1%	259	1%	6	15	21
Rest of S. America	0.98	1%	29	1%	54	1%	2	4	6
United States of America									
North	1.54	1%	312	2%	136	1%	33	12	45
South	1.37	1%	106	0%	1,266	1%	-21	106	85
West	1.54	1%	90	0%	573	1%	-6	55	49
Other	0.78	1%	754	1%	1,109	1%	35	58	93
World			9,209	1%	9,209	1%	608	658	1,266

[a] Total Economic Welfare = Consumer Surplus (CS) + Producer Surplus (PS) + policy induced Scarcity Rents (SR).

As expected, EU renewable energy policy will redirect wood pellets towards Europe. European consumption of pellets rises by 11.6 Mt, while global production increases by 9.4 Mt from the base case, with the EU's wood pellet trade deficit expanding by 2.2 Mt. From Table 3.4, the EU is projected to produce 4.3 Mt more wood pellets, but it must import more from the United States (+1.3 Mt), Canada (+1.2 Mt) and Russia (+1.1 Mt) – see Figure 3.4. At the same time, wood pellet prices are projected to rise between 71 and 147 percent depending on the region, as indicated in Table 3.4. As a result of higher wood pellet prices, consumption in the rest of the world falls by 2.2 Mt, particularly in emerging bioenergy-producing markets such as China, Japan and the U.S. Further, the global wood pellet sector gains $8.2 billion in surplus, with EU wood pellet power producers gaining $5.0 billion in consumer surplus and wood pellet producers in timber rich regions collectively gaining $1.9 billion. European reliance on imports of wood pellets will increase to 5.6 Mt, with 3.8 Mt coming from North America and 1.5 Mt from Russia.

Table 3.4: Change in wood pellet markets by selected countries/regions

	Change in:								
	Price		Consumption		Production		Economic Welfare (Mill $):		
	$/tonne		tonnes ('000s)		tonnes ('000s)		CS	PS	TOTAL[a]
Asia									
China	106.61	72%	-290	-72%	137	137%	-28	2	10
Japan	116.12	79%	-130	-78%	14	179%	-12	0	-8
Rest of Asia	109.64	74%	-1	-74%	0	85%	0	0	0
Canada									
Alberta	141.09	139%	-4	-99%	55	200%	0	4	21
Atlantic Canada	150.05	116%	-12	-90%	138	70%	-1	17	85
British Columbia Coast	136.24	126%	0	-100%	0	0%	0	0	0
British Columbia Interior	144.31	147%	-60	-99%	769	129%	-4	61	330
Rest of Canada	141.69	111%	-17	-84%	206	106%	-2	18	101
Europe									
Finland	152.37	95%	186	106%	212	78%	39	33	180
Sweden	153.96	94%	1,886	108%	1,021	69%	384	157	1,093
Rest of Europe	151.69	88%	9,551	117%	4,276	63%	1,877	659	4,954
Oceania									
Australia	137.06	126%	0	-73%	139	152%	0	12	58
New Zealand	133.35	128%	-9	-69%	39	127%	-1	3	16
Russia	138.98	88%	-386	-100%	1,109	65%	-27	188	761
South America									
Chile	118.95	82%	-32	-78%	19	47%	-3	3	10
Rest of S. America	151.69	123%	0	-87%	3	135%	0	0	1
United States of America									
North	141.09	105%	-504	-74%	334	70%	-61	32	131
South	142.51	111%	-588	-89%	785	120%	-52	89	356
West	134.05	122%	-175	-100%	151	86%	-12	19	72
Other	114.74	71%	-1	-85%	4	14%	0	0	1
World			9,411	74%	9,411	74%	2,096	1,299	8,172

[a] Total Economic Welfare = Consumer Surplus (CS) + Producer Surplus (PS) + policy induced Scarcity Rents (SR).

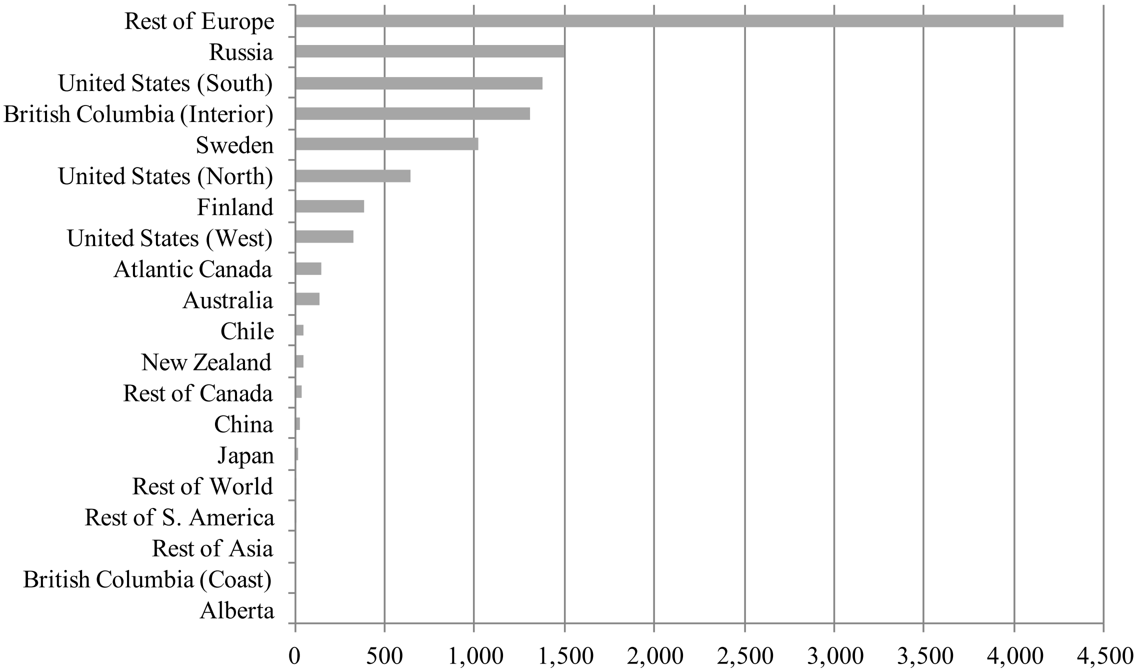

Figure 3.4: Increased wood pellet imports (‘000s tonnes) into EU member states from selected countries/regions

The global sawnwood industry is projected to benefit as a result of increased EU demand for wood pellets. Sawnwood and wood pellets are complements in production in the sense that residuals from sawmilling are used to manufacture wood pellet. As a result of increased wood pellet demand, sawmill residuals receive a higher price, effectively reducing the cost of processing logs. Global production of sawnwood is projected to rise by 3.3 million m^3, with EU and Canada leading the way with added production of 2.0 million m^3 and 0.7 million m^3 respectively. Within Canada, lumber manufacturing is redirected from Alberta to the rest of Canada, while the U.S. South experiences a reduction in sawnwood production as wood pellets are sourced directly from whole logs produced by planting additional lands to fast-growing pine, thereby reducing the need for sawmilling residuals.

The global price of coniferous sawnwood falls by \$12.04/m^3, with reductions of between 4% and 7% depending on the region or country, as indicated in Table 3.5. Globally, consumers benefit from the increase in lumber production and lower prices, gaining an estimated \$3.6 billion in additional welfare. Meanwhile, the welfare of lumber producers increases by \$400 million with a decline in producer surplus of \$20 million experienced by producers in the U.S.

South but a gain of nearly $270 million by those in the EU (see Table 3.5).

Table 3.5: Change in sawnwood markets by selected countries/regions

	Change in:								
	Price		Consumption		Production		Economic Welfare (Mill $):		
	$/m^3		m^3 ('000s)		m^3 ('000s)		CS	PS	TOTAL[a]
Asia									
China	-12.04	-5%	323	1%	65	0%	341	11	149
Japan	-12.04	-6%	151	1%	12	0%	188	2	80
Rest of Asia	-12.04	-5%	79	1%	20	0%	86	3	19
Canada									
Alberta	-12.04	-7%	21	1%	-60	-1%	21	-5	-44
Atlantic Canada	-12.04	-6%	16	1%	150	5%	18	14	16
British Columbia Coast	-12.04	-6%	17	1%	18	0%	20	2	-29
British Columbia Interior	-12.04	-7%	23	1%	443	3%	24	37	-80
Rest of Canada	-12.04	-6%	96	1%	191	2%	113	18	45
Europe									
Finland	-12.04	-5%	43	1%	10	0%	61	1	-54
Sweden	-12.04	-5%	51	1%	9	0%	71	1	-125
Rest of Europe	-12.04	-7%	1,075	1%	1,960	3%	1,069	268	791
Oceania									
Australia	-12.04	-6%	41	1%	-11	0%	53	-2	3
New Zealand	-12.04	-6%	19	1%	18	0%	21	2	-21
Russia	-12.04	-6%	186	1%	313	1%	205	34	-61
South America									
Chile	-12.04	-6%	62	1%	16	0%	55	2	-20
Rest of S. America	-12.04	-6%	118	3%	13	0%	43	1	14
United States of America									
North	-12.04	-4%	225	1%	92	3%	366	14	362
South	-12.04	-5%	127	1%	-134	0%	191	-20	-208
West	-12.04	-5%	98	1%	-45	0%	154	-7	-22
Other	-12.04	-6%	517	1%	209	1%	529	25	127
World			3,287	1%	3,287	1%	3,630	401	940

[a] Total Economic Welfare = Consumer Surplus (CS) + Producer Surplus (PS) + policy induced Scarcity Rents (SR).

Although the production of plywood and veneer also results in more residuals becoming available to wood pellet manufacturers, the amount of residual fibre impacted in this way is much smaller than that associated with sawnwood, although the direction of the effects should be similar. As indicated in Table 3.6, global production of plywood is projected by the global forest trade model to increase by an estimated 0.4 million m^3, with 28.4% coming from China. On a global scale, China has a comparative advantage in the production of plywood due, among other things, to low labour costs and available domestic sources of low cost plantation fibre used for the internal layers of plywood.

Table 3.6: Change in plywood and veneer markets by selected countries/regions

	Change in:								
	Price		Consumption		Production		Economic Welfare (Mill $):		
	$/m^3$		m^3 ('000s)		m^3 ('000s)		CS	PS	TOTAL[a]
Asia									
China	-3.68	-1%	104	0%	111	0%	94	26	38
Japan	-3.68	-1%	15	0%	3	0%	13	1	5
Rest of Asia	-3.68	-1%	7	0%	3	0%	6	1	5
Canada									
Alberta	-3.68	-1%	1	1%	-1	-1%	0	0	0
Atlantic Canada	-3.68	-1%	0	0%	1	1%	0	0	1
British Columbia Coast	-3.68	-1%	1	0%	1	0%	1	0	1
British Columbia Interior	-3.68	-1%	5	1%	17	1%	3	4	7
Rest of Canada	-3.68	-1%	3	0%	3	1%	3	1	3
Europe									
Finland	-3.68	-1%	1	0%	1	0%	1	0	-2
Sweden	-3.68	-1%	1	0%	0	0%	1	0	0
Rest of Europe	-3.68	-1%	14	0%	49	1%	17	10	25
Oceania									
Australia	-3.68	-1%	2	0%	-1	0%	2	0	1
New Zealand	-3.68	-1%	3	1%	5	0%	2	1	0
Russia	-3.68	-1%	9	1%	19	1%	5	5	5
South America									
Chile	-3.68	-1%	1	1%	3	0%	1	1	-3
Rest of S. America	-3.68	-1%	7	0%	3	0%	5	1	4
United States of America									
North	-3.68	-1%	7	0%	7	1%	6	2	8
South	-3.68	-1%	20	0%	-23	0%	18	-6	-13
West	-3.68	-1%	10	0%	-8	0%	9	-2	-4
Other	-3.68	-1%	180	0%	196	1%	144	33	87
World			391	0%	391	0%	333	77	169

[a] Total Economic Welfare = Consumer Surplus (CS) + Producer Surplus (PS) + policy induced Scarcity Rents (SR).

The world price of plywood is projected to fall by $3.68/m^3, thereby increasing world consumption by 391,000 m^3, most of which is consumed in China. Overall, plywood consumers gain $333 million of surplus, while producers gain only $77 million. Again, some plywood producing regions in the United States do not benefit from increased wood pellet demand for the same reasons mentioned with respect to sawnwood.

The global particleboard industry is projected to be adversely affected as a result of increased wood pellet use in the EU. The manufacture of particleboard utilizes planer shavings, flakes, splinters and strands that are derived from sawmill residuals and processing of pulpwood, competing for fibre with wood pellets. That is, fibre used in producing wood pellets cannot be used to produce particleboard. As a result of increased EU wood pellet demand, global supply of particleboard is reduced by 3.6 million m^3, with the majority of the loss occurring in the EU as fibre is competitively redistributed towards the production of an additional 4.3 Mt of wood pellets, at the expense of 2.3 million m^3 of particleboard. As indicated in Table 3.7, the price of particleboard is projected to rise by \$34.36/m^3 across all regions, which lowers consumption, leading to a consumer surplus loss of \$2.7 billion, with major loses in occurring in the EU (\$949 million), China (\$275 million) and the U.S. South (\$267 million). Particleboard manufacturers are adversely affected, losing some \$435 million, with the majority of this loss occurring in the EU.

Table 3.7: Change in particleboard markets by selected countries/regions

	Change in:								
	Price		Consumption		Production		Economic Welfare (Mill \$):		
	$\$/m^3$		m^3 ('000s)		m^3 ('000s)		CS	PS	TOTAL[a]
Asia									
China	34.36	10%	-353	-4%	-192	-2%	-275	-26	-68
Japan	34.36	10%	-17	-4%	-7	-1%	-13	-1	17
Rest of Asia	34.36	10%	-37	-4%	-5	-2%	-30	-1	-24
Canada									
Alberta	34.36	15%	-57	-6%	-20	-2%	-30	-3	-7
Atlantic Canada	34.36	14%	-1	-6%	0	-11%	-1	0	-1
British Columbia Coast	34.36	16%	-44	-7%	-14	-2%	-21	-2	-5
British Columbia Interior	34.36	17%	-156	-7%	-165	-8%	-72	-22	-52
Rest of Canada	34.36	14%	-165	-6%	-190	-7%	-93	-27	-71
Europe									
Finland	34.36	11%	-11	-5%	-3	-2%	-8	0	-3
Sweden	34.36	7%	-23	-3%	-8	-2%	-27	-1	-12
Rest of Europe	34.36	11%	-1,111	-4%	-2,251	-7%	-915	-257	-498
Oceania									
Australia	34.36	10%	-35	-4%	-6	-1%	-27	-1	-3
New Zealand	34.36	12%	-5	-5%	-1	-1%	-3	0	1
Russia	34.36	16%	-365	-7%	-117	-2%	-175	-16	-35
South America									
Chile	34.36	12%	-27	-5%	-13	-3%	-18	-2	-4
Rest of S. America	34.36	11%	-20	-5%	-8	-2%	-14	-1	-2
United States of America									
North	34.36	7%	-50	-3%	-84	-10%	-54	-12	-57
South	34.36	8%	-279	-4%	-124	-2%	-267	-18	-55
West	34.36	7%	-117	-3%	-72	-2%	-125	-11	-34
Other	34.36	11%	-756	-5%	-348	-2%	-551	-34	-173
World			-3,629	-4%	-3,629	-4%	-2,719	-435	-1,084

[a] Total Economic Welfare = Consumer Surplus (CS) + Producer Surplus (PS) + policy induced Scarcity Rents (SR).

Now consider fibreboard. Unlike particleboard manufacturing, to produce its panels, fibreboard manufacturers purchase wood residuals that are flat pressed. These residuals are often sourced from sawmills, but the same fibre is also used as an input into wood pellet manufacturing. Clearly, increasing wood pellet demand will create additional competition for these wood residues, which traditionally have been relied upon for producing fibreboard.

Table 3.8: Change in fibreboard markets by selected countries/regions

	Change in:								
	Price		Consumption		Production		Economic Welfare (Mill $):		
	$\$/m^3$		m^3 ('000s)		m^3 ('000s)		CS	PS	TOTAL[a]
Asia									
China	24.94	5%	-1,059	-4%	-1,287	-4%	-734	-296	-674
Japan	24.94	6%	-23	-4%	-24	-3%	-14	-6	-8
Rest of Asia	24.94	6%	-53	-4%	-17	-4%	-31	-4	-29
Canada									
Alberta	24.94	6%	-9	-4%	-6	-4%	-5	-2	-5
Atlantic Canada	24.94	6%	-2	-4%	0	-8%	-1	0	-1
British Columbia Coast	24.94	6%	-7	-4%	-5	-4%	-4	-1	-4
British Columbia Interior	24.94	7%	-20	-5%	-29	-7%	-10	-6	-14
Rest of Canada	24.94	6%	-33	-4%	-31	-7%	-19	-8	-25
Europe									
Finland	24.94	5%	-6	-3%	-3	-3%	-5	-1	-5
Sweden	24.94	2%	-3	-1%	-3	-3%	-6	-1	-6
Rest of Europe	24.94	5%	-241	-3%	-914	-7%	-172	-179	-263
Oceania									
Australia	24.94	7%	-10	-5%	-17	-4%	-5	-4	-1
New Zealand	24.94	7%	-14	-5%	-24	-4%	-7	-5	-2
Russia	24.94	6%	-78	-4%	-58	-4%	-43	-14	-36
South America									
Chile	24.94	7%	-39	-5%	-42	-4%	-20	-9	-16
Rest of S. America	24.94	7%	-40	-5%	-5	-4%	-21	-1	-20
United States of America									
North	24.94	8%	-74	-6%	-33	-8%	-30	-8	-39
South	24.94	9%	-269	-7%	-133	-3%	-97	-34	-76
West	24.94	8%	-112	-6%	-62	-4%	-46	-16	-37
Other	24.94	8%	-2,563	-6%	-1,960	-5%	-1,040	-329	-970
World			-4,655	-5%	-4,655	-5%	-2,310	-923	-2,229

[a] Total Economic Welfare = Consumer Surplus (CS) + Producer Surplus (PS) + policy induced Scarcity Rents (SR).

According to results from the forest trade model, the global fibreboard industry will be negatively affected as a result of EU renewable energy policies, with global production falling by 4.7 million m^3, reflecting scarce residual supply. Much of this lost production is attributable to China (1.3 million m^3), the EU (920,000 m^3), and other countries (2.0 million m^3). The world price of fibreboard rises by \$24.94/m^3 as global production and consumption fall by 5 percent. Prices rise by 1% to 7% depending on the region (Table 3.8). Although global production falls, producers lose a relatively smaller share than consumers, as they are able to benefit from the increased prices.

Table 3.9: Change in wood pulp markets by selected countries/regions

	Change in:								
	Price		Consumption		Production		Economic Welfare (Mill $):		
	$/tonne		tonnes ('000s)		tonnes ('000s)		CS	PS	TOTAL[a]
Asia									
China	64.99	10%	-260	-3%	-19	-3%	-508	-6	-483
Japan	64.99	11%	-212	-4%	-71	-2%	-359	-26	-127
Rest of Asia	64.99	12%	-540	-4%	-16	-3%	-838	-5	-816
Canada									
Alberta	64.99	9%	-5	-3%	-26	-3%	-11	-9	29
Atlantic Canada	64.99	8%	-1	-3%	-40	-9%	-3	-16	-11
British Columbia Coast	64.99	10%	-13	-3%	-24	-3%	-25	-9	15
British Columbia Interior	64.99	10%	-46	-3%	-262	-8%	-86	-80	-66
Rest of Canada	64.99	8%	-8	-3%	-90	-6%	-17	-33	-10
Europe									
Finland	64.99	8%	-175	-3%	-175	-2%	-395	-65	-40
Sweden	64.99	7%	-228	-2%	-213	-2%	-586	-86	-109
Rest of Europe	64.99	9%	-189	-3%	-566	-5%	-383	-208	-206
Oceania									
Australia	64.99	8%	-18	-3%	-9	-2%	-43	-3	-17
New Zealand	64.99	11%	-24	-4%	-25	-2%	-41	-8	31
Russia	64.99	10%	-146	-3%	-178	-3%	-273	-52	-49
South America									
Chile	64.99	9%	-6	-3%	-59	-3%	-12	-18	65
Rest of S. America	64.99	10%	-32	-3%	0	-3%	-63	0	-63
United States of America									
North	64.99	10%	-15	-4%	-195	-10%	-27	-66	-72
South	64.99	10%	-477	-3%	-494	-3%	-878	-154	-76
West	64.99	9%	-165	-3%	-237	-3%	-341	-83	0
Other	64.99	10%	-278	-3%	-139	-3%	-536	-33	-369
World			-2,839	-3%	-2,839	-3%	-5,422	-960	-2,374

[a] Total Economic Welfare = Consumer Surplus (CS) + Producer Surplus (PS) + policy induced Scarcity Rents (SR).

Finally, wood pellets compete for fibre with the wood pulp industry that relies on pulpwood logs, wood chips and residues that can be converted into pulp using either mechanical or chemical processes. As a result, the global wood pulp industry is projected to be adversely impacted by the EU's renewable energy policies. The wood pulp sector is project to lose \$2.4 billion in economic wellbeing (Table 3.9) as pulp production declines by 2.8 Mt globally. World prices increase by \$64.99 per tonne, reflecting a rise in regional prices anywhere between 7 and 12 percent. The most significant reductions in pulp production occur in regions that experience the largest increase in wood pellet production (EU, U.S. South and BC Interior), illustrating the impact of competition for fibre between wood pellets and pulp.

3.4 Summary and Conclusions

In this chapter, a global softwood forest products trade model was used to examine the impact of the European Union renewable energy policies as these are likely to impact the future demand for wood pellets to produce electricity (or at least a doubling of current wood pellet use). The trade model assumes global coniferous roundwood harvests and residual fibre are competitively distributed among wood processors so that the law of one price holds (Vercammen 2011). The trade model determines product prices, consumption and production, and economic welfare, throughout 20 regions. The main findings of the chapter can be summarized as follows: First, the results illustrate the important need to take into account the interconnections among forest products on a global scale – policies in any one region have positive and negative impacts on other regions. Further, while renewable energy policies that increase the demand for wood pellets may harm consumers of electricity and/or taxpayers in the region implementing these policies, they are beneficial to the forestry sector as a whole (assuming gainers can compensate losers), although there are winners and losers within this sector. The following discussion expands upon these points.

As a result of the EU's increasing demand for wood pellets, residual fibre is competitively redirected within a complex network of global forest products. The result is an increase in the world price of industrial roundwood (1%), particleboard (\$34.36/m^3), fibreboard (\$29.94/m^3), pulp (\$64.99/tonne), and pellets (71% to 128%), while the prices of sawnwood and plywood & veneer are projected to fall by \$12.04/m^3 and \$3.68/m^3, respectively. That is, the prices of wood products that produce residuals that are inputs to wood pellet manufacturing fall, while the prices of products that compete with wood pellets for fibre increase. These findings are consistent with the EEA (2007), which found that high bioenergy prices result in fibre being reallocated away from traditional sources, particularly wood pulp.

Table 3.10: Change in total forest products markets by selected countries/regions

	Change in:	
	Economic Welfare (Mill $):	
Asia		
China	-978.65	-1.1%
Japan	-24.35	-0.1%
Rest of Asia	-837.53	-4.3%
Canada		
Alberta	-9.91	-0.2%
Atlantic Canada	142.46	4.9%
British Columbia Coast	-5.19	-0.1%
British Columbia Interior	283.41	2.1%
Rest of Canada	133.00	1.0%
Europe		
Finland	109.54	0.5%
Sweden	892.59	2.8%
Rest of Europe	5,157.11	4.4%
Oceania		
Australia	49.41	0.7%
New Zealand	36.07	0.7%
Russia	705.77	2.1%
South America		
Chile	52.01	0.7%
Rest of S. America	-58.86	-1.5%
United States of America		
North	379.21	1.2%
South	12.96	0.0%
West	23.53	0.1%
Other	-1,203.79	-1.2%
World	4,858.78	1.0%

[a] Total Economic Welfare = Consumer Surplus (CS) + Producer Surplus (PS) +
policy induced Scarcity Rents (SR).

The extent to which EU renewable energy policies affect regions outside the EU is provided in Table 3.10, where the total economic welfare change in each region is highlighted. Although there are winners and losers, the global industry benefits by an estimated $4.9 billion; it should be noted that one must subtract from this the costs to electricity ratepayers and taxpayers in Europe. If only regions outside the European Union are considered, there is a net loss in overall welfare amounting to $298.3 billion, although the gains and losses are distributed unevenly between timber rich and timber poor regions. Thus, Russia, Canada and the U.S.

experience large net welfare gains or $705.8 billion, $543.8 billion and $415.7 billion, respectively, or $1,665.2 billion collectively; Asia is a net loser to the tune of $1,840.5 billion.

Finally, the difference in the welfare gain to the winners ($10.6 billion; industrial roundwood, sawnwood, plywood + veneer and wood pellet markets) and the welfare lose to the losers ($5.7 billion; particleboard, fibreboard, and pulp markets) results in a net economic welfare gain to the forest products industry of $4.9 billion. Although absent from this number, the cost associated with policy induced subsidization of bioenergy, as well as transforming an electrical grid to run on biomass, must be considered.

In fact, the price of wood pellets is projected to rise anywhere between 106.61 $/tonne to 153.96 $/tonne. The extent to which this impacts the feasibility of using wood pellets in producing bioenergy is outside the scope of this chapter, yet deserves attention. The EU has mandated renewable energy targets to be achieved by the year 2030 (2030 Policy Framework for Climate and Energy), while many coal-fired power plants in the province of Ontario have been retrofitted to run off biomass in the near future (Ontario Green Energy Act). However, aggressive implementation of such policies could well undermine this particular renewable energy strategy as wood pellet prices double or much more in our scenarios.

Some potential shortfalls of this chapter include the inaccuracy of the primary source of data FAO (2012), yet it is used for its comprehensive coverage of the global forest products industry. Further work may wish to expand upon the softwood model to include non-coniferous fibre; however, the substitutability between species is difficult to model and may bring more uncertainty into the framework. Overall, the results presented in this chapter are sensitive to the numerical framework employed including assumptions made in regards to the model parameters.

The main source of uncertainty in the findings of this chapter is derived through the arbitrary scenario that considers a double of EU wood pellet demand as a result of renewable energy targets within the EU. Countries are expected to pursue renewable energy targets in line with their initial resource endowment. The method employed in this chapter assumes a uniform ‘doubling’ of the current wood pellet demand in all EU regions. Certainly, the projected effects on prices, consumption, production, and trade are sensitive to the exogenous shock, and more work is needed in forecasting the actual increase in wood pellet demand in EU region.

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Chapter 4

OPPORTUNITIES IN THE ENERGY SECTOR: USING FOREST PRODUCTS TO REDUCE EMISSIONS AND HARNESS NEW MARKETS

4.1 Introduction

Many countries are hoping to transform their energy sectors away from coal power to renewable sources to reduce their carbon dioxide (CO_2) emissions. One option is to co-fire biomass with coal to reduce the CO_2 emissions intensity of coal plants. Co-firing biomass in existing coal-fired power plants is appealing due to the low incremental investment required to retrofit established facilities and because energy produced from biomass is considered to be carbon neutral (IPCC 2006). Under the IPCC reporting rules the impacts of energy produced from biomass would not be reported in the energy sector but in the Agriculture, Forestry and Other Land-Use (AFOLU) sector (previously the LULUCF sector). Carbon emissions from biomass energy are considered carbon neutral since the IPCC Guidelines assumes that carbon lost during harvest equals carbon gained through re-growth, so there are no net CO_2 contributions. With this in mind, it is estimated that 234 coal-fired power plants have been retrofitted to co-fire with biomass on a commercial basis (IEA Bioenergy Task 32, 2009).

The increased demand for biomass energy has resulted in the creation of new wood product markets, primarily in the form of wood pellets. Driven largely by EU policies, global wood pellet production has increased from 1.7 million tonnes (Mt) in 2000 to 15.7 Mt in 2010

(Lamers et al. 2012), largely for use in the European market.[13] Although Europe is also a large producer, there is little capacity to increase European pellet production. As a result, the wood pellet manufacturing sector in Canada has emerged as a significant supplier, exporting 1.9 Mt to Europe in 2011.[14] In fact, Canada currently exports 90% of its wood pellet production to Europe. As of 2012, British Columbia (BC) had 1,875,000 tonnes of wood pellet manufacturing capacity, accounting for 65% of Canadian capacity and production (WPAC 2012). This sector has traditionally utilized low-cost mill residuals as feedstock, but significant increases in production will require incorporation of more costly fibre from forest operations.

In particular, as a result of these European incentives, BC exported 840,000 tonnes of wood pellets to the UK and 240,000 to the Netherlands in 2012 (Industry Canada, 2013). There are numerous risks to expanding or even maintaining exports of pellets from BC to Europe, including potential changes in European energy policies, the rapid rise of exports from low-cost competitors and relatively high shipping costs. With this in mind it is logical to examine potential new markets as a hedge against too large an exposure by its growing pellet manufacturing sector to the European market. Especially when considering the high degree of policy risk associated with pellet exports to Europe.

A logical market may be developing close to home. Under the Copenhagen Accord, Canada agreed to reduce its greenhouse gas (GHG) emissions by 17% from 2005 levels by 2020.Currently, coal-fired electricity generation in Canada is responsible for 77% of the GHG emissions from the electricity sector, despite generating only 15% of the electricity supply. With this in mind, the Government of Canada (2011), through an amendment to the Canadian Environmental Protection Act (1999), imposed an emissions intensity standard for generating

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[13] European countries have agreed on a binding target to achieve a 20% share of renewable energy in total energy consumption by 2020. Co-firing biomass with coal is becoming more common in EU countries, with the Netherlands, the UK and Belgium leading the way. These countries have implemented various incentives for retrofitting coal plants. In the Netherlands, power producers receive a feed-in-tariff of €67/MWh under the 2002 MEP (Milieukwaliteit van de Elektriciteits Productie). In the UK, electricity generators are required to obtain 12% of their energy from renewable sources, including biomass. It uses Renewable Obligation Certificates (ROC) to incentivize retrofitting of coal plants to co-fire biomass; the average price an ROC was €55.9/MWh in 2012. Similarly, Belgium relies on Green Certificates (average price in 2012 of €118/MWh) to encourage large-scale retrofitting of coal plants.

[14] http://www.pellet.org/production/production (accessed July 10th, 2013).

electricity from thermal power plants, although it would initially apply only to new plants and those refurbished because of their age. The standard was set at an emissions intensity level commensurate with that for high-efficiency combined-cycle gas turbines (CCGT). Initially it was set at 375 tCO_2 GWh^{-1}, but it was later raised to 420 tCO_2 GWh^{-1}.

In addition to the changing electricity generating landscape in Ontario[15], the Alberta electricity sector will inevitably play a major role if Canada is to comply with the Copenhagen Accord, as it has 5,795 MW of installed coal-fired capacity representing 53% of its current electricity output. In 2007, Alberta became the first jurisdiction in North America to put a price on carbon; it introduced what amounted to (but was not called) a carbon tax that targeted large industrial emitters. These industries are required to reduce their carbon emissions intensity by 12 per cent or pay a \$15-per-tonne tax on CO_2 emissions. A recent government proposal could see the tax increase to \$40/tCO_2 in hopes of mitigating emissions by 28%[16]. It is estimated that companies currently pay \$1.80/tCO_2 and that this would rise to \$16/tCO_2 if the tax were increased (Kleiss 2013).[17]

While Alberta and BC (which has no coal plants) have carbon taxes (albeit of different forms), the EU and Ontario rely on feed-in-tariffs (FiT) that are implemented as a premium paid to energy produced from biomass. Unlike a carbon tax, which penalizes emission-intensive technologies across the board, a feed-in-tariff is designed to encourage investment in renewable

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[15] Ontario had earlier (2007) mandated elimination of coal power by 2014, with financial incentives for biomass energy production. Subsequently, the Green Energy and Green Economy Act (2009) introduced a feed-in-tariff scheme for electricity generated from renewable sources, including a subsidy on biomass electricity of between 13 and 13.8 ¢/kWh. This subsidy has recently increased to 15.6 ¢/kWh, effective August 26, 2013. As a result, two coal-fired power plants are currently undergoing a retrofit to allow power generation from biomass – including Nanticoke Generating Station, which just a few years ago, was the largest coal-fired power plant and one of the largest single sources of emissions in North America. In anticipation of the 2014 coal phase out, Ontario's capacity to convert biomass residuals to wood pellets is increasing at unprecedented rates. Currently, there are three wood pellet plants under construction in Ontario, with seven more proposed (Canadian Biomass, 2013). These plants are strategically located near large sawmills to benefit from the residuals associated with lumber production.

[16] The Alberta Environment Minister Diana McQueen has proposed what is known as the "*40/40 plan*", which would come into effect by 2020 and raise the emissions reduction target to 40% and increase the carbon price to C\$40 a tonne.

[17] Unless otherwise indicated, all monetary units are in Canadian currency.

energy technologies. As a result, it is expected that reliance on a carbon tax as opposed to a feed-in-tariff will result in much a different optimal generating mix.

In this chapter, we focus on the externality associated with CO_2 emissions. This way, we can examine the optimal investment in generating assets in response to market incentives. We use the Alberta energy sector as our case study as it is heavily invested in fossil fuel assets. Additionally, Alberta's proximity to BC allows it to have access to a significant amount of wood pellet manufacturing capacity for co-firing biomass with coal. Indeed, this may provide an opportunity for BC to expand its market while reducing its exposure to the risk of changes in foreign energy policies. In response to increasing demand for climate change mitigation while providing reasonably priced electricity, co-firing may be beneficial for both Alberta and British Columbia.

The objectives of the current research are therefore (1) to examine the impact of different market incentives for encouraging the co-firing of biomass with coal; (2) to investigate the potential of reducing CO_2 emissions through co-firing biomass with coal; and (3) to determine the feasibility of marketing BC wood pellets in Alberta.

4.1.1 Carbon Tax vs. Feed-in Tariff

To see how these policies affect the optimally installed capacity, first consider Figure 4.1 below which depicts 2012 hourly load in panel (a); panel (b) displays a load-duration curve which is created by sorting the 2012 hourly load in descending order.

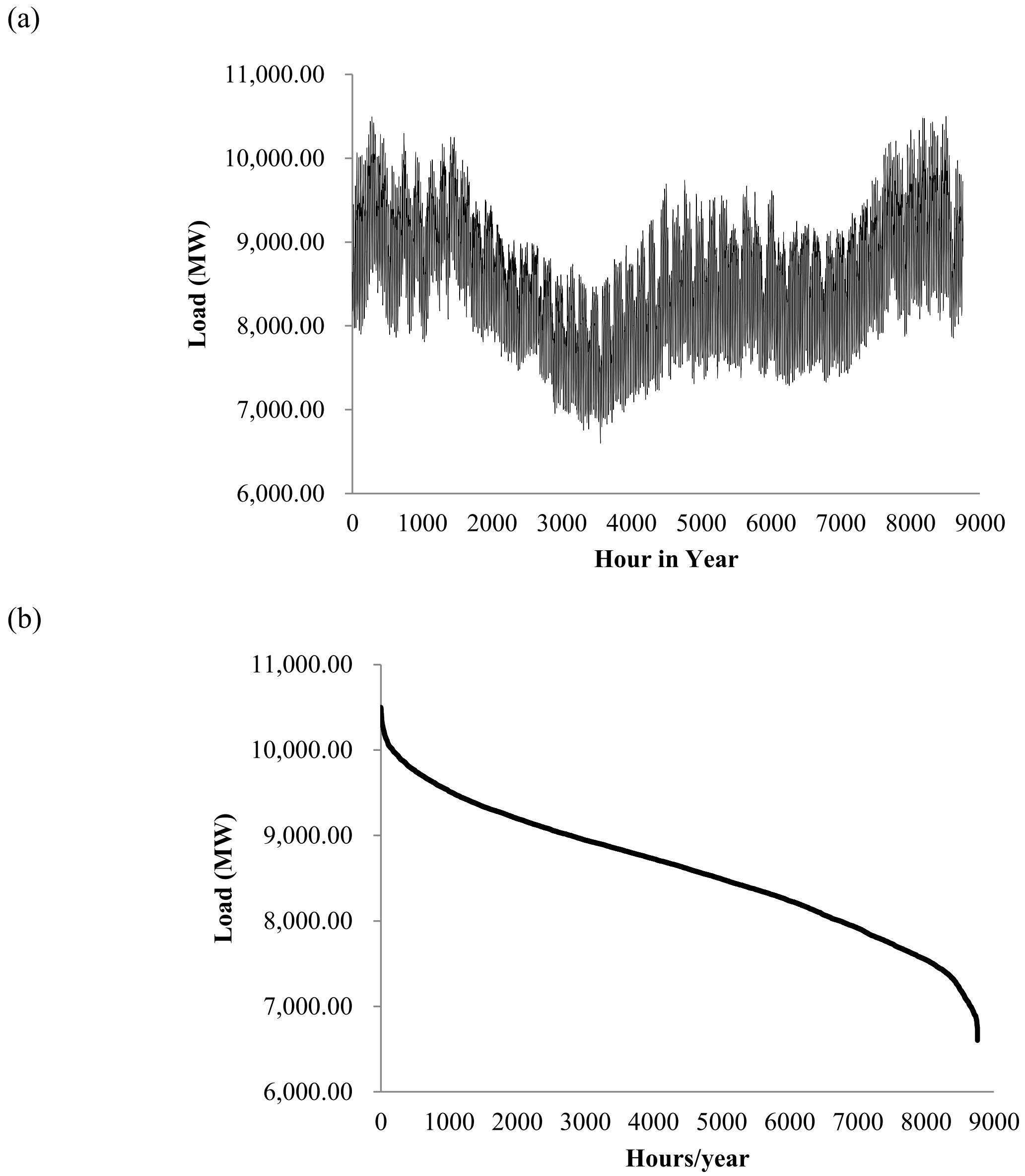

Figure 4.1: (a) 2012 Alberta load curve; and (b) 2012 Alberta load curve ordered into a load-duration curve.

Next, one can construct screening curves, representing the average capacity cost of a specific generating technology. A screening curve is a graphical representation where time (in hours) is represented on the horizontal axis, and total cost (in dollars) on the vertical axis. Total cost is comprised of two specific parts: the initial capital expense; and the operating expense per hour. The capital expense of installing the capacity is represented as the total amortized cost (including interest) of installing the capacity, indicated as the vertical intercept. The per-hour operating expense (operating and maintenance as well as fuel costs) determines the slope of the screening curve. To simplify the screening curves, the slope representing the per-hour operating expense is a linear approximation – a constant variable cost.

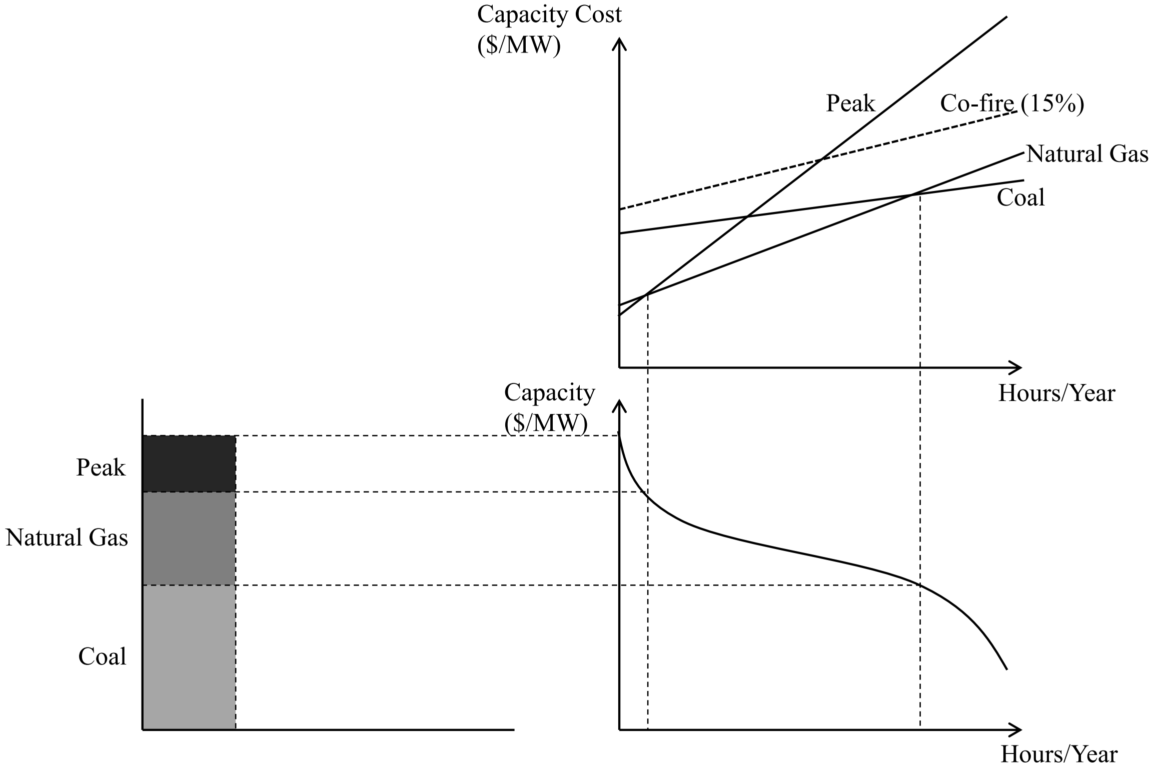

Figure 4.2: Optimally installed generation capacities based on screen curves and a load duration curve: absent of government policy

The top right of Figure 4.2 represents four screening curves: a coal plant representing a typical base-load plant; a natural gas plant representing a combined-cycle gas turbine mid-load plant; a peak-load plant representing an open-cycle gas turbine; and a co-fire plant representing a base-load plant relying on 15% fuel from wood pellets and 85% from coal. The bottom of Figure 4.2 depicts the amount of capacity each technology should provide as part of the optimally installed generating mix.

From Figure 4.2, we see that the base-load coal plant has high capital costs but low operating expenses per hour. To offset this high capital cost, the coal plant must rely on its low operating expense, ensuring it maintains a high capacity factor.[18] The peak-load plant has a low capital cost combined with a high operating expense, making a low capacity factor optimal for this asset. The mid-load plant is somewhere between the coal and peak plant, thus operates at a capacity factor in between that of coal and peak-plants. Finally, it is not optimal to co-fire biomass with coal as the per-hour operating expense is currently not low enough to offset the initial capital cost at any capacity factor.

Without government policy, co-firing biomass with coal may not be included in the optimally installed generating mix. This chapter will focus on two policies for encouraging the co-fire of biomass and coal for energy production: a tax on carbon; and a feed-in-tariff on electricity produced from co-firing biomass with coal. As previously mentioned, Alberta has a \$15-per-tonne tax on CO_2 emissions, while other jurisdictions (Ontario and the many countries within the EU) rely on a feed-in-tariff in order to encourage renewable investments.

First, the impact of a carbon tax on the optimally installed generating mix can be analyzed using load-duration and screening curves. Figure 4.3 depicts a situation with a carbon tax (\$/tCO_2), punishing emission intensive technologies. Although the initial capital expenditure required for each respective generating asset is unchanged, the carbon tax will affect the per-hour operating costs of fossil fuel technologies (i.e. the slope of the screening curves). In fact, the more emissions intensive the generating asset, the greater the increase in per-hour operating expense. Table 4.2, in section 4.3.1, provides a summary of the factors contributing to the per-hour operating costs of a variety of technologies, including their respective emissions intensities.

All generating assets in Figure 4.3 experience an increase in per-hour operating expense as a result of the tax on carbon emissions. As coal is the most emissions intensive technology, its respective slope is most affected.[19] Meanwhile, mid-load natural gas is the least emissions intensive asset, resulting in a less affected per-hour operating expense.[20] Peak-load gas turbines

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[18] The capacity factor of a power plant is calculated as the ratio between its actual output to its potential output, for a given time period. It is assumed that it is possible for the asset to operate at full capacity indefinitely.

[19] Approximately 961 tCO_2/MWh in Alberta in 2012 (Environment Canada, 2013).

[20] Approximately 420 tCO_2/MWh in Alberta in 2012 (Environment Canada, 2013).

have emissions intensity somewhere between coal and mid-load natural gas, resulting in an increase in the slope of the screening curve somewhere in the middle. Finally, the emissions intensity of co-firing is dependent on the proportion of biomass included in fueling the electricity generation. This is possible since carbon emissions produced from burning sustainably managed biomass are not accounted for in the electricity sector, reducing the effective emissions intensity of such a plant. Thus, co-firing at a 15% rate will result in a per-hour operating expense (slope of the screening curve) to be less steep than that of coal, possibly allowing co-firing to become cost effective at high capacity factors.

Under a carbon tax scenario identified in Figure 4.3, co-firing becomes part of the optimally installed generating mix. As a result of the emissions intensity of coal, its high initial capital expense is no longer offset by its low per-hour operating expense to the degree which it was, absent of government policy - we see a reduction in coal capacity. However, co-firing at 15% is able to offset the high initial capital expense with relatively lower per-hour operating costs (compared to coal alone), resulting in co-firing capacity to become optimal. Peak-load gas capacity is reduced due to its relatively high emissions intensity; meanwhile mid-load natural gas capacity may increase, to offset some of the lost capacity from reduced coal capacity.

A carbon tax may be used to achieve a goal of encouraging co-firing into the optimally installed generating mix. However, it is unclear from Figure 4.3 whether this finding will be consistent across varying levels of carbon tax. As the tax becomes higher, the greater the impact on per-hour operating expense for emission intensive technologies, pushing them out in favour of lower emitting sources like mid-load natural gas.

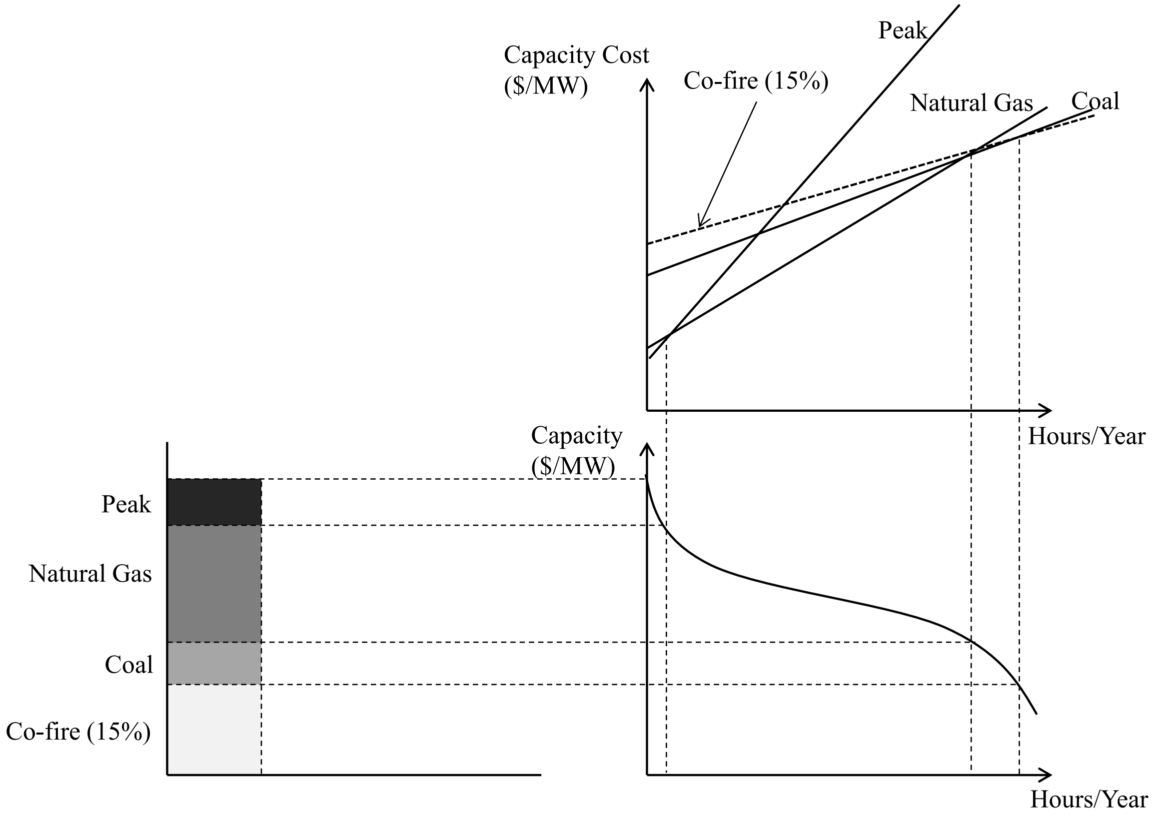

Figure 4.3: Optimally installed generation capacities based on screen curves and a load duration curve: under a carbon tax scenario

In contrast, a feed-in-tariff is specifically designed to encourage investment in renewable energy technologies such as biomass power production. In fact, this policy is already in place within the EU and Canada to encourage the retrofitting of coal-plants to co-fire biomass.[21] Although renewable energy sources can be effective in mitigating climate change, they typically face relatively high generating costs compared to their fossil-fuel counterparts. Implementing a feed-in-tariff on renewable energy sources by subsidizing electricity generated on a per-kWh basis lowers their per-hour operating expense.

Unlike a carbon tax, a feed-in-tariff from electricity produced from biomass will only

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[21] As mentioned, the Netherlands, the UK and Belgium all have some form of subsidy in place for electricity generated from biomass. In Ontario, a feed-in-tariff program has been established under the Green Energy Act subsidizing biomass energy production at 13-13.8 ¢/KWh.

affect the per-hour operating expense of co-firing. An increase in the feed-in-tariff will result in a lower per-hour operating expense of co-firing (i.e. a flatter screening curve). The screening curves for all other generating assets will be unaffected, maintaining their original position as outlined in Figure 4.2. With a feed-in-tariff, coal capacity may be driven out in favour of co-firing, while mid-load and peak-load natural gas capacity is relatively unchanged. As a larger feed-in-tariff is applied to this scenario, co-firing will likely become more and more significant in terms of optimal capacity.

The Alberta Electric System has an objective to meet load requirements within Alberta at the lowest possible cost. As a result, the analysis conducted using screening curves will be a significant driver of the choice of optimal generating assets. However, the problem with this simplification is that capacity costs are not the only consideration at play. Other factors include the availability of fuel, ramp rates due to load variability, electricity trade across interties to other jurisdictions, and other technical and engineering constraints. Thus, considering capacity costs alone is inadequate for modelling optimal generating assets and a numerical mathematical programming model is required instead; this model is developed in Section 4.2. Nonetheless, the analysis presented in this section offers an excellent way to illustrate how different market instruments offer incentives to invest in renewable energy sources, like biomass.

4.2 Numerical Model of Alberta Generating Grid

To assess the objectives outlined in section 1, a mathematical programming model is developed for the Alberta electricity grid with a 750 MW link to BC. We expand an earlier model of the Alberta electricity grid by van Kooten, Johnston and Wong (2013) by integrating a spatial model of wood pellet production in British Columbia and Alberta. Each individual coal-fired power plant within Alberta may decide to retrofit to co-fire with biomass. A carbon tax or feed-in-tariff is used to promote such a transition, as outlined in Section 4.1.1.

Alberta's power system is completely deregulated, with the Alberta Electric System Operator (AESO) using prices and knowledge about load and power output to allocate generation across assets. Although private firms make decisions on the basis of prices, the model we develop assumes the AESO decides on the decommissioning of extant fossil-fuel generation assets, investment in new natural gas assets, and retrofitting of current coal-fired generating capacity to co-fire with biomass and coal. Electricity trade between Alberta and British Columbia is dictated through price differentials as well as intertie transmission constraints.

In essence, the AESO is assumed to maximize annual profit subject to load, trade and engineering constraints.

The profit function can be written as follows:

$$\Pi = \sum_{t=1}^{T} \begin{bmatrix} P_{A,t} D_t - \sum_i VC_i \times Q_{t,i} + \\ \sum_{BC} \begin{Bmatrix} \left(P_{A,t} - (P_{A,t} - P_{BC,t} - \delta) M_{BC,t} \right) \\ + \left(P_{BC,t} - (P_{BC,t} - P_{A,t} - \delta) X_{BC,t} \right) \end{Bmatrix} \end{bmatrix} - \sum_i \sum_r \left[\left(W_{r,i} KM_{r,i} \alpha \right) + \sum_t \left(P_{w.t} W_{t,i} \right) \right] \tag{4.1}$$

$$- \sum_i (a_i - d_i) \Delta C_i ,$$

where Π is profit ($); *i* refers to the generation source (viz., natural gas, coal, retrofitted coal, wind, or hydro); *T* is the number of hours in one-year (8760); D_t refers to the demand or load that has to be met in hour *t* (MW); $Q_{t,i}$ is the electricity produced by generator *i* in hour *t* (MW); CF_i is energy proportion of biomass to coal in a retrofitted coal plant (only applicable to current coal generating capacity); OM_i is operating and maintenance cost of generator *i* ($/MWh); and b_i is the variable fuel cost of producing electricity using generator *i* ($/MWh), which is assumed constant for all levels of output. We define $P_{j,t}$ to be the price ($/MWh) of electricity in each hour, with j ={A, BC} referring to Alberta and British Columbia, respectively. While Alberta prices vary hourly, the BC price is fixed. $M_{BC,t}$ is the amount imported by Alberta from British Columbia at *t*, while $X_{BC,t}$ is the amount exported from Alberta to British Columbia; δ is the transmission cost ($/MWh). Additionally, τ is a carbon tax ($ per tCO_2), and φ_i is the CO_2 emitted per MWh of electricity from generation source *i*. Finally, *F* refers to the feed-in-tariff ($ per MWh) of electricity produced from biomass in co-firing plant *i*.

The first term on the RHS of (4.1) refers to the operations of the power market and the middle term to the pellet plants, with the final term depicting the annualized cost of adding or removing capacity. VC_i refers to the variable cost of electricity produced from generator *i*, excluding the variable costs associated with wood pellets, and is calculated as:

$$VC_i = OM_i + (1 - CF_i)(b_i + \tau\varphi_i) - CF_i \times F .$$

Wood pellet costs are represented in the last term of the top line in (4.1); $W_{r,i}$ refers to tonnes of wood pellets purchased from pellet producer r (discussed below), destined for retrofitted co-firing plant i; $KM_{r,i}$ is the distance from pellet producer r to pellet consuming generating source i (kms); α represents the transport cost adjustment for one tonne over one kilometre (tonne-km); $P_{w,t}$ represents the FOB mill pellet price (\$/tonne) in hour t; and $W_{t,i}$ represents the number of pellets required in time t to co-fire with coal in generator i. Specific information on wood pellet prices are presented in section 4.3.1.

In addition, C_i refers to the capacity of generator i (MW). The bottom line (last term) in (4.1) permits the addition or removal of generating assets, where a_i and d_i refer to the annualized cost of adding or decommissioning assets (\$/MW), and ΔC_i is the capacity added or removed. For wind assets, ΔC_W is measured in terms of the number of wind turbines added, each with a capacity of 2.3 MW. Given that wind energy is non-dispatchable ('must run'), a sink, S_t, is assumed available in each period where excess energy can be directed or retrieved if the system cannot respond quickly enough. Further, R_i is the amount of time it takes to ramp production from plant i. Transmission between jurisdictions is constrained depending on whether power is exported or imported; import and export constraints are denoted TRM_{BC} and TRX_{BC}, respectively.

Objective function (4.1) is maximized subject to the following constraints:

Demand is met in every hour:

$$\sum_i Q_{t,i} + \sum_{BC} \left(M_{BC,t} - X_{BC,t} \right) - S_t \geq D_t, \forall t = 1,...,T. \tag{4.2}$$

Ramping-up constraint:

$$Q_{t,i} - Q_{(t-1),i} \leq \frac{C_i}{R_i}, \forall i, t = 2,...,T. \tag{4.3}$$

Ramping-down constraint:

$$Q_{t,i} - Q_{(t-1),i} \geq -\frac{C_i}{R_i}, \forall i, t = 2,...,T. \tag{4.4}$$

Capacity constraints:

$$Q_{t,j} \leq C_i, \ \forall\, t,i. \tag{4.5}$$

Import transmission constraint:

$$M_{BC,t} \leq TRM_{BC},\ \forall\, t = 1,...,T. \tag{4.6}$$

Export transmission constraint:

$$M_{BC,t} \leq TRK_{BC},\ \forall\, t = 1,...,T. \tag{4.7}$$

Non-negativity:

$$Q_{t,i},\ \mathrm{M_{BC,t}},\ \mathrm{X_{BC,t}} \geq 0,\ \forall\, t,i,k. \tag{4.8}$$

The amount of wood pellets (tonnes) required in a given hour to supply a retrofitted coal-biomass power plant must equal the amount of electricity generated (MWh) for a given rate of co-fire (% electricity from wood pellets). λ is a measure of heat content for wood pellets, approximately 5 MWh/tonne (EIA, 2012). To represent this, the following constraint is used:

$$PR_{t,i} \leq CF_i Q_{t,i}/\lambda\ \forall\, t,i. \tag{4.9}$$

In addition, the pellets received (tonnes) at a retrofitted co-firing plant must meet the required amount of pellets (tonnes) to adequately generate electricity. This constraint is formalized as the following:

$$\sum_r W_{r,i} = \sum_t PR_{t,i}\ \forall\, r,t,i. \tag{4.10}$$

The amount of wood pellets (tonnes) shipped from pellet producing facility *r* must be no greater than the pellet producing capacity of such a plant. *pcap*$_r$ is the capacity (in tonnes) of pellet producer *r* (details below). The following constraint is used:

$$\sum_i W_{r,i} = pcap_r\ \forall\, r,i. \tag{4.11}$$

In any given hour, electricity can only flow in one direction along the Alberta-BC transmission intertie. To model this and avoid a nonlinear constraint, we assume that $TRM_{BC} = TRX_{BC} = TCAP_{BC}$, and then employ the following linear constraint to limit the flow to one direction:

$$X_{BC,t} + M_{BC,t} \leq TCAP_{BC,t}, \ \forall t. \tag{4.12}$$

Some 1,200 GWh of hydroelectricity is produced annually in Alberta, with more than 70% constituting non-dispatchable run-of-river output. The remainder is generated by two dams used primarily for flood control. Although their capacity factors are less than 10%, a small subcomponent of the model simulates the operation of a hydro facility so that the system has some capacity to store wind generated electricity. A description of the hydroelectric subcomponent is found in Louck, Stedinger and Haith (1981).

It is assumed that all generators of a given type operate efficiently, with only the marginal generator's output fluctuating (ramping) up and down as needed. Generators that are not needed are removed, although decommissioning of capacity is assumed to be continuous. Further, the added costs of shutdown and start-up of thermal power plants associated with wind variability are not taken into account. The decision variables in the model are $Q_{t,i}$ (including the decision to retrofit a coal plant to co-fire with biomass), $M_{BC,t}$, $X_{BC,t}$, ΔC_i, $PR_{t,i}$, and $W_{r,i}$, with the latter two pertaining to wood pellets.

4.3 Data

The Alberta energy grid in 2012 is spread across 4,164 MW of natural gas base-load generating capacity, 1,500 MW of peak-load natural gas plants, 900 MW of hydroelectric generating capacity, 1,123 MW of generating capacity associated with approximately 490 wind turbines; 409 MW of biomass; and 5,795 MW of coal-fired generating capacity. This coal capacity is distributed across 16 coal-fired power plants (with six providers), with an average emissions intensity of 961 tCO_2/GWh as outlined in Table 4.1.

Table 4.1: Installed coal-fired capacity in Alberta, 2012

Station Unit	Capacity	Completed	CO_2 (t/GWh)[a]	NOx (t/GWh)[a]	SO_2 (t/GWh)[a]
Battle River					
3	150	1969	931	1.9	5.5
4	150	1975	882	1.8	5.4
5	389	1981	1,176	2.4	5.0
Genesee					
1	410	1989	980	2.0	2.0
2	410	1994	980	2.0	2.0
3	495	2005	676	0.7	0.9
HR Milner					
1	158	1972	1,103	2.3	3.0
Keephills					
1	396	1983	1,103	2.3	2.1
2	396	1983	1,127	2.3	2.1
3	495	2011	676	0.7	0.6
Sheerness					
1	390	1986	1,127	2.3	6.4
2	390	1990	1,127	2.3	6.4
Sundance					
3	408	1976	980	2.0	1.8
4	386	1977	931	1.9	1.8
5	386	1978	833	1.7	2.0
6	386	1980	784	1.6	2.0

[a] Source: Environment Canada (2013)

Coal-fired generating stations in Alberta are optimally located near coal mines, as well as transmission lines connected to load centers. However, coal-fired generating units within Alberta differ based on location, age, efficiency and capacity. For example, the oldest coal unit in Alberta is Battle River 3, which was completed in 1969, with an emissions intensity of 931 tCO_2 GWh^{-1}. Meanwhile, Keephills 3 came on-line in 2011, with an emissions intensity of 676 tCO_2 GWh^{-1} (see Table 4.1).

The optimally installed capacity will depend not only on fuel costs, but also emissions efficiencies as well as the age of the plant such that retrofit costs can be amortized over a longer period of useful life. In addition, the location of a coal plant relative to a wood pellet producer will inevitably turn out to be a significant driver of whether a plant chooses to retrofit. Increased hauling costs result in increased average generating costs through increased delivered wood pellet costs.

The capacity of the intertie between Alberta and BC varies with direction, but we simply assume a single transmission capacity constraint of 750 MW. BC is dominated by hydroelectricity that accounts for 11,000 MW or 92.4% of BC's generating capacity and its hydro reservoirs have the capacity to store energy from Alberta.

Electricity demanded within Alberta has a significant amount of weekly and seasonal variation. The average annual load during 2012 was 8,203 MW with a maximum of 10,610 MW and a minimum of 6,829 MW. Electricity prices for Alberta and BC are used to determine movements along the interties. In 2012, market clearing electricity prices averaged $90/MWh in Alberta, ranging from a low of $0 to a high of $1,000. The BC system is not de-regulated so prices are unknown; thus, we assume a fixed BC price of $75/MWh based on information from contracts with independent power producers and BC Hydro's expected future costs.

4.3.1 Technical Details

It is estimated that 234 coal-fired power plants have been retrofitted to co-fire with biomass on a commercial basis, with a majority co-firing at rates below 15% (IEA Bioenergy Task 32, 2009). In most cases, plants retrofitted to co-fire on a continual basis, do so at rates around 5 to 15 percent (IEA Clean Coal Centre, 2012). Indeed, co-firing proportions in conventional pulverized coal-plants have increased from roughly 1% to 10% of energy input to over 20% in the past decade (IEA Bioenergy Task 32, 2009). Recent studies suggest that substitution of coal for biomass can readily be achieved for levels up to 50%, depending on the co-firing technique (DENA, 2011; Vattenfall, 2011; IRENA, 2013). Direct co-firing with pre-milled wood pellets in pulverized coal-fired boilers allows for greater flexibility in co-fire rates. However, it should be noted that co-firing at high rates might lead to efficiency losses due to fouling and slagging associated with corrosion (IEA Bioenergy Task 32, 2009; IRENA, 2012). This could significantly increase operating costs.

Table 4.2: Construction and Operating Costs ($2012), CO_2 Emissions, and Ramp Rates of Various Generating Assets

		Construction Costs[a]		Variable Costs ($/MWh)[b]			
Asset	Years to build	Overnight ($/kW)	Decommission as % of overnight	O&M[a]	Fuel	Emissions intensity (tCO_2 MWh^{-1})	Ramp rate % of capacity per hour[e]
Coal	4	2658.0	24.0	4.25	7.75	0.936[d]	2.5
Retrofit	1	274.0	24.0	n.a.	n.a.	n.a.	2.5
Wind	3	1300.0	n.a.	0.00	0.00	0.015	n.a.
Hydro	4	2134.0	n.a.	2.55	1.01	0.009	n.a.
CCGT	3	927.0	10.0	9.87	14.69[b]	0.420	7.5
OCGT	2	634.0	10.0	14.70	19.56[c]	0.600	12.5

[a] EIA, 2012
[b,c] Henry Hub Spot Price (average, 2012)
[d] Average emissions intensity of coal plants within Alberta as of 2012. Emissions data from Environment Canada
[e] Estimates based on AESO (2010, p.13) and total system ramp rate of 600 MW per hour

This chapter examines a range of co-firing rates. In this way, current coal-fired capacity within Alberta can be relied upon with only minor retrofit costs. Co-firing at these rates requires a capital investment for boiler modifications and fuel handling. Information on construction and operating costs, CO_2 emissions and ramping rates for generators are provided in Table 4.2. The overnight construction cost of 'retrofit' refers to the incremental investment required to transform an already existing direct feed coal-fired generating station to run on a combination of coal and biomass as a fuel source.

4.3.2 Wood Pellets

The wood pellet industry in western Canada is dominated by British Columbia, with minor productive capacity in Alberta. British Columbia is home to approximately 1.9 Mt of wood pellet manufacturing capacity, centred primarily in the central and northern regions of the BC Interior (Table 4.3). In fact, this industry has grown substantially in recent years, with two new manufacturing plants established in the last year (Merritt and Kamloops). British Columbia is looking to take advantage of this expanding market with two new proposed plants in Northern BC, providing an additional capacity of over 200,000 tonnes per year (Canadian Biomass, 2013).

Table 4.3: Estimated Cost of Transporting Wood Pellet from Producer to Power Plant ($/tonne)

Pellet Producer		**Coal-Fired Power Plant**					
Province *Location*	**Capacity (tonnes/yr)***	*Battle River*	*Genesee*	*HR Milner*	*Keephills*	*Sheerness*	*Sundance*
British Columbia							
Merritt	90,000	57	51	43	49	53	48
Kelowna	50,000	52	47	48	48	47	48
Kamloops	35,000	52	46	38	44	48	43
Prince George	400,000	47	42	34	40	57	39
Armstrong	50,000	47	43	44	44	43	44
Burns Lake	400,000	66	55	47	53	70	52
Strathnaver	200,000	57	46	38	44	61	44
Quesnel	90,000	60	48	40	46	63	45
Williams Lake	150,000	63	52	44	50	64	49
Houston	150,000	71	60	52	57	75	57
Vanderhoof	140,000	59	48	40	45	63	44
Princeton	90,000	62	56	48	54	58	53
Vanderhoof	30,000	59	48	40	45	63	44
Alberta							
Grande Cache	25,000	35	24	10	22	43	21
La Crete	60,000	51	46	39	45	58	43
Slave Lake	60,000	25	17	29	16	32	16
Total Capacity	2,020,000						

* Biomass Wood Markets, 2013

Estimates of $/tonne based on Super B-train grain truck, hauling a maximum of 44 tonnes

Wood pellet manufacturing in British Columbia is ideally located in close proximity to sawmill residue supply from lumber manufacturing, as well as increased fibre supply from un-merchantable timber from the mountain pine beetle infestation. Nevertheless, the fuel cost associated with wood pellets to generate power is sensitive to the distance between the power plant and pellet mill. Table 4.3 provides estimates of the transport costs from pellet producers to coal-fired power plant in Alberta ($/tonne). This calculation is based off estimated trucking costs of a Super B-train grain truck, which is an 8-axle configuration with two trailers, hauling 44 tonnes of wood pellets. On average, wood pellets from within BC have an estimated transportation cost of $51 per tonne to an Albertan coal-fired power plant, while sourcing pellets from within Alberta has an average estimated transport cost of $32/tonne.

It is assumed that a retrofitted co-firing power plant in Alberta must pay at least as much as what a pellet manufacturer would receive by shipping overseas. Wood pellet prices are provided in Figure 4.4; prices averaged \$135.88/tonne (FOB from the Port of Vancouver) in 2012, reaching a high of \$140.25/tonne and a low of \$130/tonne. Since this price includes the shipping cost from the pellet producer in the BC interior to Vancouver, average shipping costs of \$41.93 per tonne during this period need to be subtracted, thereby providing an average FOB mill price of \$93.95/tonne (Argus Biomass Markets, 2012). Thus, to obtain prices in Alberta, it is necessary to add the cost of transporting pellets from the BC mill to an Alberta power plant (Table 4.3). The average fuel cost of wood pellets for Albertan coal-fired power plants is approximately \$27.18/MWh.

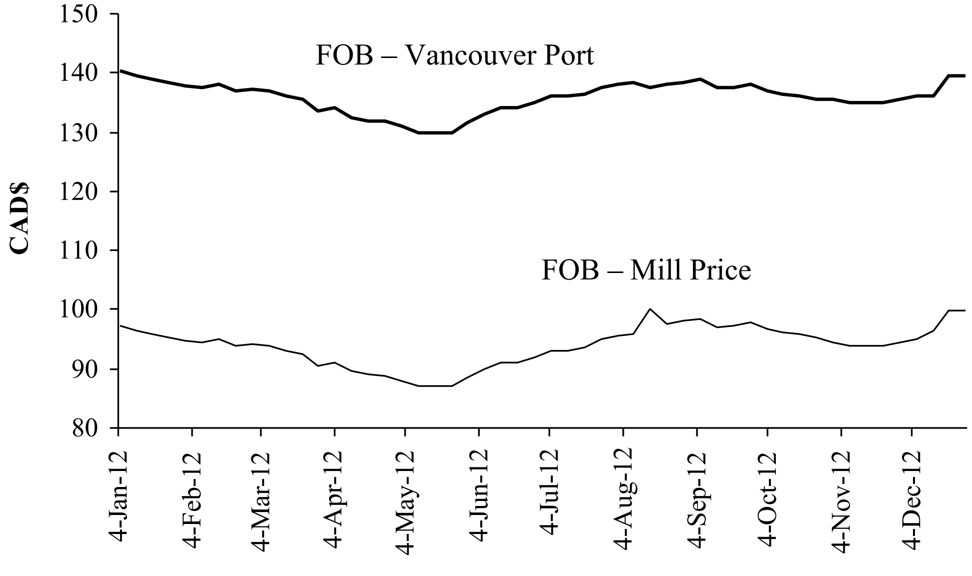

Figure 4.4: Wood Pellet Prices (CAD\$ per Tonne), Weekly 2012
Source: Argus Biomass Markets

4.4 Model Results

To understand how Alberta's generating mix might respond to policies that aim to achieve these emissions-intensity targets, we employ a carbon tax that varies from \$0 to \$200 per tCO_2. This policy is compared to the use of a feed-in-tariff that varies from \$0 to \$120 per MWh of biomass energy produced. A feed-in-tariff is a more common market incentive to encourage the transition towards biomass energy generation. In essence, we wish to determine the regulatory regimes under which the energy sector in Alberta is able to compete with the EU for British Columbian wood pellets. As well, we will examine the different effects a tax and a subsidy have on the optimal generating grid in Alberta, with the ability to co-fire coal with biomass.

4.4.1 Capacity and Generation

First, consider the impact of a carbon tax on the optimal generation mix in Alberta. In Table 4.4, the current generating mix is provided in the first row, while the optimal results under different policy scenarios are provided in the following rows. As indicated in section 2, it appears as though there are lower and upper carbon tax thresholds in which co-firing may be optimal. Further, if the co-firing rate is too low, it will never be optimal to retrofit a coal plant.

In Table 4.4, the carbon tax drives a majority of the pure-fired coal out of the generating mix, for either a 5% or 15% co-fire rate. Under both co-firing rates, coal capacity declines from 5,795MW to 359MW as the carbon tax increases from \$0 to \$200 tCO_2. Regardless of the co-firing rate, as the carbon tax increases to \$200 per tCO_2, 3,100 MW of new natural gas capacity is added because it is relatively cheaper to build and operate due to low fuel costs as well as relatively low emissions intensity.

If we were to co-fire at a 5% rate of biomass as fuel, co-firing would never be the optimal choice under a carbon tax scenario. Due to the small amount of biomass as a percent of total fuel, the reduction in the effective emissions intensity is insignificant. As a result, the benefit of co-firing (avoided carbon taxes) falls below the required retrofit cost, thus never allowing co-firing at 5% to become the optimal choice.

If we increase the co-fire rate to 15%, it becomes optimal to retrofit up to 3,398 MW of currently installed coal capacity to co-fire with biomass. At a carbon tax of \$50 tCO_2, the avoided carbon tax associated with co-firing at 15% outweighs the retrofit cost to convert a coal plant to use both biomass and coal. In fact, at this level, 800 MW of natural gas peak-load generation is also removed. In addition, average electricity generating costs are \$5.71/MWh lower with the 15% co-fire scenario than they are for the 5% scenario, assuming a carbon tax of \$50 per tCO_2. These savings represent the low retrofit cost required to allow biomass and coal to be co-fired in current coal capacity, along with reduced applicable carbon taxes through lower emissions intensities.

Table 4.4: Optimal Generating Capacities, Various Scenarios, MW

Co-fire Rate Scenario *Policy*	Co-fire	Coal	CCGT[a]	OCGT[a]	Electricity Cost ($/MWh)	Wood Pellets (tonnes)
Initial	0	5,795	4,164	1,500	21.70	0
5% Co-fire Rate						
Carbon tax						
$0	0	5,795	4,164	1,500	21.70	0
$50	0	5,795	4,164	739	59.07	0
$100	0	590	7,165	1,500	122.20	0
$150	0	929	7,090	1,500	139.68	0
$200	0	359	7,265	1,500	161.09	0
Feed-in-Tariff						
$0	0	5,795	4,164	1,500	21.70	0
$30	0	5,795	4,164	1,375	21.70	0
$60	0	5,795	4,164	1,375	21.70	0
$90	5,795	0	4,164	1,418	35.84	507,576
$120	5,795	0	4,164	1,418	34.90	507,576
15% Co-fire Rate						
Carbon tax						
$0	0	5,795	4,164	1,500	21.70	0
$50	3,398	1,736	4,164	699	53.36	890,185
$100	990	0	6,417	1,500	115.48	228,972
$150	0	929	7,090	1,500	139.68	0
$200	0	359	7,265	1,500	161.09	0
Feed-in-Tariff						
$0	0	5,795	4,164	1,500	21.70	0
$30	95	5,700	4,164	1,375	22.15	25,000
$60	5,795	0	4,164	1,418	34.32	1,522,842
$90	5,795	0	4,164	1,418	31.52	1,522,842
$120	5,795	0	4,164	1,418	28.71	1,522,842

[a] CCGT and OCGT refer to base-load and peak-load natural gas facilities, respectively

When the carbon tax becomes too high, lower emitting natural gas pushes coal electrical generation out of the mix, with no biomass entering whatsoever. Under the 15% co-firing rate, this appears to happen at a carbon tax somewhere above $\$100/\text{tCO}_2$. Although co-firing with biomass allows coal capacity to lower their emissions intensity, it is offset by the substantial carbon payments made at high carbon tax rates. At such rates, there are cost savings in transforming the electrical grid towards lower emitting natural gas.

Now, if a feed-in-tariff is used as a financial instrument to encourage currently installed coal capacity to co-fire with biomass, we see a much different picture. First, under both low and high rates of co-firing, a large enough feed-in-tariff is successful at encouraging co-firing capacity to enter the optimal generating grid. Highlighted in Table 4.4, a feed-in-tariff of \$60/MWh does not provided enough of a financial incentive to retrofit coal plants to co-fire at 5%. Meanwhile, if we allow co-firing up to 15%, then a similar feed-in-tariff encourages 5795MW of coal capacity to be retrofitted. Since the feed-in-tariff is effectively a subsidy on energy produced from biomass, the greater the co-firing rate, the greater the subsidy received.

Since a carbon tax affects all fossil fuel generating assets, it results in a very high average generating cost (\$/MWh) to meet the load requirements in Alberta. The most co-firing capacity added while using a carbon tax is under a tax of 50 \$/tCO2 while co-firing at a 15% rate. Under this rate, 3398MW of coal capacity is retrofitted to co-fire with biomass, using 890,185 tonnes of wood pellets. The price on carbon will impact a significant amount of the generating sector within Alberta, resulting in an average price of electricity of \$53.36/MWh. Meanwhile, co-firing at a similar 15% rate with a \$60/MWh feed-in-tariff on biomass results in a retrofit of all the currently installed coal capacity. Under this scenario, 1.5 Mt of wood pellets are required to fuel the 5795 MW of co-firing capacity, more than under any carbon tax scenario. At this point, the average generating cost of meeting Alberta load requirements is only \$34.42/MWh. Since a feed-in-tariff only targets biomass specifically, it is able to encourage a greater amount of co-firing capacity, at a much lower generating cost to Alberta.

4.4.2 Reducing Carbon Dioxide Emissions

Although a feed-in-tariff is more successful at encouraging biomass co-firing in currently installed coal capacity, it is unclear how successful the policy is at reducing GHG emissions.[22] The reason is, although a feed-in-tariff specifically targets biomass energy production, it does not target GHG emissions. Table 4.5 provides emissions and abatement costs found for optimal

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[22] GHG emissions are calculated consistent with IPCC Guidelines (2006). That is, CO_2 emitted as a result of biomass energy production is not accounted for in the energy sector, as it has already been accounted for in the Agriculture, Forestry and Other Land-Use (AFOLU) sector. This accounting procedure is used to avoid double counting of CO_2 emissions.

generating mixes in Alberta, under various regulatory regimes.

Table 4.5: Total Emissions and Abatement Costs under Various Scenarios

Scenario Policy	5% Co-fire		15% Co-fire	
	Emissions (Mt CO_2)	Abatement Cost (\$/tCO_2)	Emissions (Mt CO_2)	Abatement Cost (\$/tCO_2)
Carbon tax				
\$0	56.5	n.a.	56.5	n.a.
\$50	45.6	262.18	42.6	253.06
\$100	32.2	323.30	33.5	318.08
\$150	29.9	348.41	29.9	348.41
\$200	29.9	410.99	29.9	410.99
Feed-in-Tariff				
\$0	56.5	n.a.	56.5	n.a.
\$30	56.5	n.a.	56.4	240.33
\$60	56.5	n.a.	49.8	287.48
\$90	54.3	715.74	49.8	321.48
\$120	54.3	749.39	49.8	355.37

There are two trends that are apparent from the emissions output provided in Table 4.5. First, a tax on carbon in the electricity generating sector leads to lower optimal CO_2 emissions than those found when relying on a feed-in-tariff on biomass electricity production. In fact, the lowest amount of optimal CO_2 emissions found in Alberta under a carbon tax is a substantial 20 Mt lower than that found under a feed-in-tariff. In fact, there is virtually no realistic combination in which a feed-in-tariff on biomass results in lower emissions from the Alberta electricity sector than relying on a carbon tax. At \$90 and \$120 per MWh of feed-in-tariff, co-firing capacity is constrained by current coal capacity. In other words, additional co-firing capacity would have to be built new, eliminating the benefit of the low incremental investment related to relying on currently installed coal-fired infrastructure. Even if this were not the case, current wood pellet manufacturing capacity will inevitably be maxed out.

The second trend, which can be identified from Table 4.5, is a tax on carbon emissions is more cost effective than a feed-in-tariff on biomass in reducing CO_2 emissions. Consider a co-fire rate of 15%, a carbon tax of \$50 per tCO2 results in 42.6 Mt of emissions - costing \$253.06 per avoided tCO_2. Meanwhile, a feed-in-tariff of \$120/MWh reduced emissions to only 49.8 Mt of CO_2 - costing \$355.37 per avoided CO_2. Since abatement costs increase with the feed-in-tariff (and carbon tax for that matter), it is clear that any higher feed-in-tariff will inevitably result in a higher abatement cost.

4.4.3 Impact of Canadian Coal-fired Performance Standards

By 2015, when the regulation[23] comes into effect, it is expected that Alberta will have 5795 MW of installed coal-fired generating capacity spread over 6 generating stations and 16 independent units. Of these units, 7 will be affected by the new regulations within the first ten years. As identified in Table 4.6 in bold, this consists of 2024 MW of currently installed generating capacity.

To examine how this policy will impact the optimal generating mix in Alberta, as well as the potential for relying on co-firing as a compliance strategy, this scenario has been integrated in the numerical model outlined in Section 4.2. The difference being, the current emissions intensity of these units is 961 tCO_2 GWh^{-1} – over double that of the 420 tCO_2 GWh^{-1} standard. As a result, to comply with the new regulations while satisfying energy demanded in Alberta, the 7 units affected by the policy will either have to co-fire at 56% or shut down entirely in favour of alternative generating sources like natural gas.

As mentioned in Section 4, most co-firing is done at, or below 15%. However, there are examples of fully converted pulverized coal plants relying on high rates of direct co-fired generation. Unit #4 of the 'Les Awirs' power plant in Belgium was fully retrofitted to burn biomass for upwards of 100% of its 80-MW capacity; this was followed, in 2011, with the retrofit of the 200-MW capacity unit #4 of the 'Rodenhuise' coal plant to burn only biomass. In Denmark, the 250-MW unit #1 of the 'Amager' facility can now directly co-fire biomass with coal at ratios ranging from zero to 100% of boiler capacity.

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[23] Through an amendment to the Canadian Environmental Protection Act (1999), the Government of Canada (2012) imposed a performance standard for generating electricity from coal-fired power plants23, although it would initially apply only to new plants and those refurbished because of their age. The standard was set at an emissions intensity level commensurate with that for high-efficiency combined-cycle gas turbines (CCGT) - initially set at 375 tCO_2 GWh^{-1}, but later raised to 420 tCO_2 GWh^{-1}.

Table 4.6: Age and Capacity of Coal-Fired Units in Alberta – Units Affected by Canadian Regulations within First 10 Years in Bold

	Established	Capacity	Age in 2015	Useful Years Left by 2015
Battle River				
3	**1969**	**150**	**46**	**-1**
4	**1975**	**150**	**40**	**5**
5	1981	389	34	11
Genesee				
1	1989	410	26	19
2	1994	410	21	24
3	2005	495	10	35
HR Milner				
1	**1972**	**158**	**43**	**2**
Keephills				
1	1983	396	32	13
2	1983	396	32	13
3	2011	495	4	41
Sheerness				
1	1986	390	29	16
2	1990	390	25	20
Sundance				
3	**1976**	**408**	**39**	**6**
4	**1977**	**386**	**38**	**7**
5	**1978**	**386**	**37**	**8**
6	**1980**	**386**	**35**	**10**

Bold indicates generating units affected by the Canadian coal-fired regulations within the first ten years of policy implementation (2015-2025)

In fact, there are two co-fired, direct feed power plants in Canada. The 'Nanticoke' generating station (4,000-MW capacity) in Ontario is a retrofitted pulverized coal plant that recently completed test runs with biomass generating up to 100% of the plant's capacity. Ontario's 'Atikokan' power plant (230-MW capacity) has also completed tests using wood pellets co-fired with coal; these tests have been successful at generating 100% capacity with biomass fuel. The latter station was converted to co-fire high rates of biomass at a cost of $200 million, or at a retrofit cost of $870/MW.

With this in mind, co-firing at high rates of co-fire has not yet been tested for any significant period of time. There are many uncertainties regarding high rates of co-firing including fouling and slagging associated with corrosion, as well as securing long term biomass supply. In this case study, we assume co-firing at a rate of 56% in order to comply with the new regulations will come at a retrofit cost of $870/MW – equal to that recently experienced in Ontario. As well, the long-term biomass supply is assumed to be constrained by the current wood pellet manufacturing capacity in Alberta and British Columbia.

As outlined in Table 4.7, the optimal generating mix in Alberta is dependent on whether or not the option to co-fire exists, as well as the regulatory environment in place. The 'initial' scenario highlights the current generating mix, as of 2012. All other scenarios listed below 'initial' represent situations whereby the Alberta generating mix must comply with the coal-fired performance standards set to come in line in 2015. In other words, these scenarios force the 7 generating units indicated in bold in Table 4.6 to either retrofit to co-fire to reduce their respective emissions intensity commensurate to the performance standard, or shut down.

Table 4.7: Optimal Electrical Generating Assets for Meeting Coal-Fired Performance Standards in Alberta

Scenario *Policy*	Co-fire	Coal	CCGT	OCGT	Electricity Cost ($/MWh)	Emissions (Mt CO2)	Abatement Cost ($/tCO2)	Pellets (tonnes) ($/tCO2)
Initial	0	5,795	4,164	1,500	21.70	56.54	n.a.	n.a.
No Co-fire	n.a.	3,771	4,164	1,500	36.84	47.77	135.79	n.a.
Co-fire								
Current	495	3,771	4,164	1,500	41.17	47.45	169.92	484,998
Carbon tax								
$50	2,024	3,771	4,164	810	76.94	36.87	221.45	1,985,328
$100	2,024	599	3,196	1,500	108.88	30.66	265.50	1,985,328
$150	2,024	934	3,263	1,500	126.75	28.44	295.01	1,984,637
$200	2,024	357	3,087	1,500	147.18	28.34	351.51	1,984,107
Feed-in-Tariff								
$30	2,024	3,771	4,164	1,375	49.21	47.61	250.90	1,985,616
$60	2,024	3,771	4,164	1,375	52.86	47.61	284.25	1,985,622
$90	2,024	3,771	4,164	1,375	56.39	47.61	316.38	1,986,007
$120	2,024	3,771	4,164	1,375	60.04	47.61	349.73	1,986,007

Once co-firing is no longer constrained from entering the generating grid in Alberta, identified under the 'Co-fire' scenario in Table 4.7, it is optimal to co-fire under any policy environment, at least to some degree. The 'Current' policy scheme under the 'Co-fire' scenario indicates an environment in which no additional policies have been implemented under this scenario in order for Alberta to comply with the standards while meeting the electricity demand obligations. Here, it is optimal for 495 MW of currently installed coal-fired generating capacity to co-fire with biomass. The remaining 1529 MW of coal capacity subject to the performance standards are shut down. In the end, Alberta demands 484,998 tonnes of wood pellets manufactured from Alberta and British Columbia.

The 495 MW of installed co-fired capacity is spread across three generating units: 158MW in H.R. Milner; 61 MW in Sundance 4; and 275 MW in Sundance 5. Although 85,000 tonnes of wood pellets are sourced from within Alberta to fuel these generating units, 400,000 tonnes per year are sourced from British Columbia. Due to its proximity, Alberta demands all of these wood pellets from the current wood pellet producer in Prince George. As a result, 129,993 tonnes of wood pellets annually are shipped to H.R Milner and 270,077 tonnes annually to Sundance 5. Meanwhile, the remainder of the annual wood pellet demand is sourced from within Alberta. H.R. Milner demands an additional 25,000 tonnes annually from Grand Cache, while Sundance 4 exclusively sources its wood pellets from Slave Lake at 60,000 tonnes annually. The average delivered price of wood pellets is $123.95, which equates to roughly $24.79 per MWh.[24]

The following policies of ‘Carbon tax’ and ‘Feed-in-tariff’ represent scenarios where the option to retrofit to co-fire is enabled, with various carbon taxes and feed-in-tariffs used as financial incentives to co-fire. All of the 2024 MW of affected coal capacity is retrofitted to co-fire under the varying levels of carbon taxes, as well as feed-in-tariffs. However, the amount of remaining optimal coal capacity is significantly lower under higher rates of carbon taxes, than it is for any level of feed-in-tariff. As a carbon tax punishes emissions regardless of the source, this policy again leads to significantly lower emissions than any feed-in-tariff on biomass.

All scenarios with either a carbon tax, or feed-in-tariff, require just shy of 2.0 Mt of wood pellets, generating approximately 10 TW of electricity from biomass. The optimal wood pellet shipments for a feed-in-tariff of $30 per MWh of electricity produced from biomass are provided in Table 4.8. As any regulatory environments considered in Table 4.7 retrofit all 7 affected coal plants to co-fire, the shipments provided in Table 4.8 are consistent with all scenarios. The wood pellet manufacturing sector in Alberta is fully utilized, while 98% of British Columbia’s wood

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[24] This calculation is based off 1 tonne of wood pellets produces 4.8-5.2 MW of electricity.

pellet manufacturing capacity is required to fuel the co-firing plants in Alberta. As a result, 145,000 tonnes of wood pellets are derived from within Alberta, while 1,841,014 tonnes are sourced from British Columbia. In fact, Battle River Unit 4, and Sundance Unit's 3, 5, and 6, depend solely on British Columbian wood pellets.

Table 4.8: Optimal Wood Pellet Shipments to Supply Alberta Co-fired Generators Subject to Performance Standards & FiT of $50/MWh

Pellet Producer		**Affected Coal-Fired Power Plant**						
Prov.	**Capacity**	**Battle River**		**HR Milner**	**Sundance**			
Location	**(tonnes/yr)***	*Unit 3*	*Unit 4*	*Unit 1*	*Unit 3*	*Unit 4*	*Unit 5*	*Unit 6*
British Columbia								
Merritt	90,000	0	0	0	0	0	0	90,000
Kelowna	50,000	37,185	12,815	0	0	0	0	0
Kamloops	35,000	0	0	0	13,468	21,532	0	0
Prince George	400,000	0	134,370	0	265,630	0	0	0
Armstrong	50,000	50,000	0	0	0	0	0	0
Burns Lake	400,000	0	0	0	0	21,244	378,756	0
Strathnaver	200,000	0	0	130,035	0	69,965	0	0
Quesnel	90,000	0	0	0	0	0	0	90,000
Williams Lake	150,000	0	0	0	91,244	0	0	58,756
Houston	150,000	0	0	0	0	116,014	0	0
Vanderhoof	140,000	0	0	0	0	0	0	140,000
Princeton	90,000	0	0	0	0	90,000	0	0
Vanderhoof	30,000	0	0	0	30,000	0	0	0
Alberta								
Grande Cache	25,000	0	0	25,000	0	0	0	0
La Crete	60,000	60,000	0	0	0	0	0	0
Slave Lake	60,000	0	0	0	0	60,000	0	0
Total Capacity	2,020,000	147,185	147,185	155,035	400,343	378,756	378,756	378,756

* Biomass Wood Markets, 2013

Depending on hauling costs, delivered wood pellet prices vary from as low as $127.86 per tonne for H.R. Milner, to as high as $147.98 per tonne for Sundance Unit 5. Based upon the optimally determined shipments, the hauling cost for H.R. Milner is $31.79 per tonne, while the same cost for Sundance Unit 5 is $51.91 per tonne. Considering all 7 co-firing units, the average delivered wood pellet price is $141.05 per tonne, or approximately $28.21 per MW.

It may be unclear whether or not a feed-in-tariff will be the best choice for Alberta. On one hand, average generating costs using a feed-in-tariff of $30 per MWh are $8.04/MWh higher than if no additional policy was in place ($49.21 vs $41.17). However, due to the coal-fired regulations, the optimal generating grid in Alberta may result in lower total generating capacity if no additional policy is put in place. In the first ten years of the performance standard implementation, if no additional policy is used, it is optimal for 1529 MW of coal capacity to shut down, while only 495 MW of co-firing capacity is added. In fact, this scenario leads to the lowest amount of total installed generating capacity in Alberta, whereby Alberta relies heavily on imports from British Columbia over a 750 MW intertie. Meanwhile, a feed-in-tariff results in 1,404 MW more electricity generating capacity than if no additional policy was in place. This allows for greater electrical independence from British Columbia, driven mainly through 2024 MW of retrofitted co-firing capacity.

4.5 Concluding Discussion

In light of the external costs associated with CO_2 emissions, and the favourable treatment of CO_2 emissions from using biomass for energy, electricity generating grids around the world are co-firing biomass with coal in retrofitted coal-fired power plants in order to reduce their effective emissions intensities. What makes this feature appealing is the low incremental investment required to transform a grid currently dominated by coal into one which utilizes a combination of coal and biomass. With this in mind, 234 coal-fired power plants have been retrofitted to co-fire with biomass on a commercial basis.

Although co-firing relies on an economical retrofit of current coal capacity, financial incentives such as a carbon tax, or a feed-in-tariff on biomass produced energy, have been used to encourage coal dominated generating grids to transition towards this lower emitting fuel combination. Both policies can be used to encourage co-firing biomass with coal to be the optimal generating strategy, leading to increased costs of generation. Although average generating costs are substantially higher under a carbon tax than a feed-in-tariff, it leads to a generating mix with lower CO_2-emitting sources like natural gas. Unlike a feed-in-tariff, a carbon tax may push the option to co-fire out in favour of lower emitting fossil-fuel sources like natural gas.

A large barrier to co-firing biomass with coal is securing the supply of biomass. As transportation costs are a significant driver of the economics behind co-firing, proximity to fibre is a potential barrier. With this in mind, the Alberta-BC case study is used to identify the feasibility of co-firing, as well as the impacts of using a carbon tax or a feed-in-tariff to further encourage coal plants to retrofit. Alberta currently is dominated with coal-fired power generation, while British Columbia has a significant amount of wood pellet manufacturing capacity.

In lieu of an emissions standard on coal-fired power generation, co-firing may be a cost effective compliance strategy. Relying on a case study of a Canadian performance standard on coal-fired power plants of 420 tCO_2 GWh^{-1}, co-firing in Alberta may be the optimal choice in meeting demand requirements. Independent of any policy, our results indicate the optimal generating grid within Alberta will choose to retrofit approximately 500 MW of currently installed coal capacity to co-fire with biomass in order to reduce its effective emissions intensity commensurate with the forthcoming performance standard. As a result, almost 500,000 tonnes of wood pellets are required per year to fuel these generators.

The production of wood pellets has increased dramatically in recent years due, in large part, to aggressive emissions policy in the EU. In the last decade, Canada has benefitted from this growing trend by increasing exports overseas, adding value to its forest product sector. With the potential development of domestic demand in Alberta, some of this wood pellet production in BC may be reallocated away from its traditional export destination, the EU. In fact, our results indicate that in light of the pending performance standard on coal-fired power plants in Canada, there could be as much as 500,000 tonnes of wood pellets shipped from BC to Alberta. This represents approximately 25% of all wood pellet shipments Canada previously made to the EU in 2012.

BC wood pellet producers will export to the region that yields the highest price for wood pellets, and thus, Alberta will need to match the price offered from the EU. Re-directing half a million tonnes of wood pellets from the EU towards Alberta will likely have an impact on the globally traded price. However, the EU has been diversifying its suppliers of wood pellets in recent years, with the US, Russia, and parts of Asia and South America increasing shipments to the EU. Combining this with the fact Canada traditionally represented less than 10% of total wood pellet supply to the EU indicates the impact on prices is likely to be small.

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Chapter 5

BACK TO THE PAST: BURNING WOOD TO SAVE THE GLOBE

5.1 Introduction

In an effort to reduce carbon dioxide (CO_2) emissions from fossil fuel burning, renewable energy policies have promoted 'carbon neutral' biomass as an energy source. Carbon flux from burning biomass is often legislated or simply assumed to be carbon neutral as subsequent growth sequesters carbon from the atmosphere (IPCC, 2006). Yet trees may take decades to recover the CO_2 released by burning, so assumed emissions neutrality implies that climate change is not considered an immediate threat. That is, the carbon neutrality of biomass hinges on the fact that we count CO_2 removals from the atmosphere equally independent of when they occur, and that such removals offset emissions. When there is greater urgency to address climate change, however, more emphasis should be placed on immediate removals of CO_2 from the atmosphere and much less on removals that occur in the more distant future.

How pressing is climate change mitigation? According to the latest UN Intergovernmental Panel on Climate Change (IPCC) report, the "observed impacts of climate change are widespread and consequential" (IPCC, 2014). The U.S. National Climate Assessment (NCA) reiterated the warnings of the IPCC regarding climate change, suggesting that a once distant concern is now a pressing one as future climate change is largely determined by today's choices regarding fossil fuel use (NCA, 2014).

To reduce current emissions of CO_2 from fossil fuel burning, many countries intend to substitute biomass for coal in existing coal-fired power generators, with some already having done so. This is an appealing option because burning biomass in existing coal plants requires relatively low retrofitting costs. Thus, 234 coal plants had already been retrofitted to co-fire with biomass (wood pellets) on a commercial basis by 2009 (Cremers, 2009). Biomass use in coal plants is bound to increase as more countries will need to rely on its assumed neutrality to meet their CO_2 emission reduction targets (Lamers et al., 2012).

In Europe, for example, countries originally agreed to a binding target that requires 20% of total energy to come from renewable sources by 2020 (Directive 2009/28/EC). Then, in early 2014, the European Commission proposed a new framework with a more ambitious EU-wide renewable energy target of 27% by 2030. While wind turbines and solar panels are the face of such efforts, Europe expects one-half or more of its renewable energy target to come from biomass (European Commission, 2013). To meet these targets, member states have individually adopted a variety of domestic policies to promote energy from biomass, including feed-in tariffs, a premium on market prices and/or tradable renewable energy certificates (RES-LEGAL, 2014). As indicated in Figure 5.1, these measures are expected to increase European consumption of wood pellets to an estimated 38 Mt yr^{-1}, requiring significant imports of pellets from outside the EU.

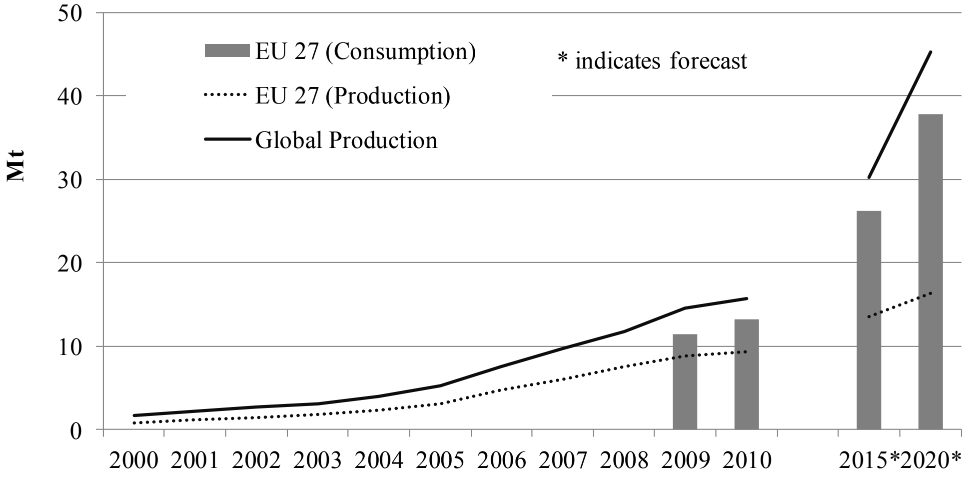


Figure 5.1: Production and consumption of wood pellets in the EU-27 (Mt),2000-2010 and forecasts for 2015 and 2020
Source: Lamers et al., 2012; Pöyry, 2011

In Canada, performance standards on coal-fired power plants now impose an upper limit on emissions of 420 kg CO_2 MWh^{-1} – equivalent, according to government, to new highlyefficient combined-cycle gas turbines. The standard applies to combustion of coal and its derivatives, and “all fuels burned in conjunction with coal, except for biomass” (Canada Gazette 2011). This leaves open the option of blending ‘zero-emissions’ biomass to the point where the standard is met. As of 2014, two large-scale Canadian power plants have been retrofitted to run on ‘carbon neutral’ biomass, including the Nanticoke Generating Station that was the largest coal-fired power plant and one of the largest single sources of emissions in North America.

In the United States, a recent ruling by the Environmental Protection Agency in September 2013 (EPA, 2013) requires new coal plants to have carbon capture and storage (CCS) capability, or otherwise achieve a particular performance standard. While the construction cost of CCS-capable plants is prohibitive, evidence from other studies (e.g., Riddel and Shaw, 2003) suggests that the costs of compensating citizens to take on the risks of storing CO_2 will make CCS not only economically unattractive but a definite dead end. Further, the CCS process increases the energy required to produce electricity by some 28% (EIA, 2013). Again, co-firing biomass with coal is viewed as an alternative compliance strategy to achieve emission intensity in coal plants of 500 kg CO_2 MWh^{-1} (Edenhofer et al., 2011; World Nuclear Assoc., 2011).

As biomass energy continues to be a significant strategy for transitioning away from fossil fuels, the question becomes: To what extent should we value future atmospheric carbon removals? In particular, as climate change mitigation has become a timely matter, what contribution does future carbon uptake in forests ecosystems make to the mitigation of climate change? The purpose of this chapter is to examine the assumptions and pitfalls of biomass carbon sequestration in light of its increasing use as a fossil-fuel alternative. This chapter demonstrates that the assumed carbon neutrality of biomass for energy production hinges on the fact that we weakly discount future removals of carbon, and it is sensitive to tree species and the nature of the fuel for which biomass substitutes.

5.2 Methods and data

In Figure 5.2, we illustrate how biomass is assumed to be carbon neutral, and in particular, how it may be used to reduce CO_2 emissions from fossil fuel burning. The release of CO_2 is depicted on the ordinate with time on the abscissa. The CO_2 emitted by burning fossil fuels to generate, say, one MWh of electricity results in a one-time increase in atmospheric CO_2 denoted by a negative value and, assuming no decay of atmospheric CO_2, illustrated by the horizontal dotted line. Assume that biomass is instead burned to generate that one MWh of electricity at time $t = 0$; this results in more CO_2 emissions than would occur with the burning of fossil fuels – a significant point discussed in more detail below. Unlike fossil fuels, however, newly planted trees then begin to remove CO_2 from the atmosphere. At time $t = M$, the cumulative carbon flux from the biomass source will equal that from the fossil fuel source, and eventually should exceed it for $t > M$; by substituting biomass for fossil fuels, less CO_2 is emitted into the atmosphere because growing trees removes CO_2 from the atmosphere and stores it as carbon in biomass. At some future time, say $t = N$, tree growth removes as much CO_2 from the atmosphere as was added by burning the biomass at time $t = 0$. Carbon neutrality is thus based on the assumption that CO_2 released by burning wood is subsequently removed from the atmosphere by growing biomass.

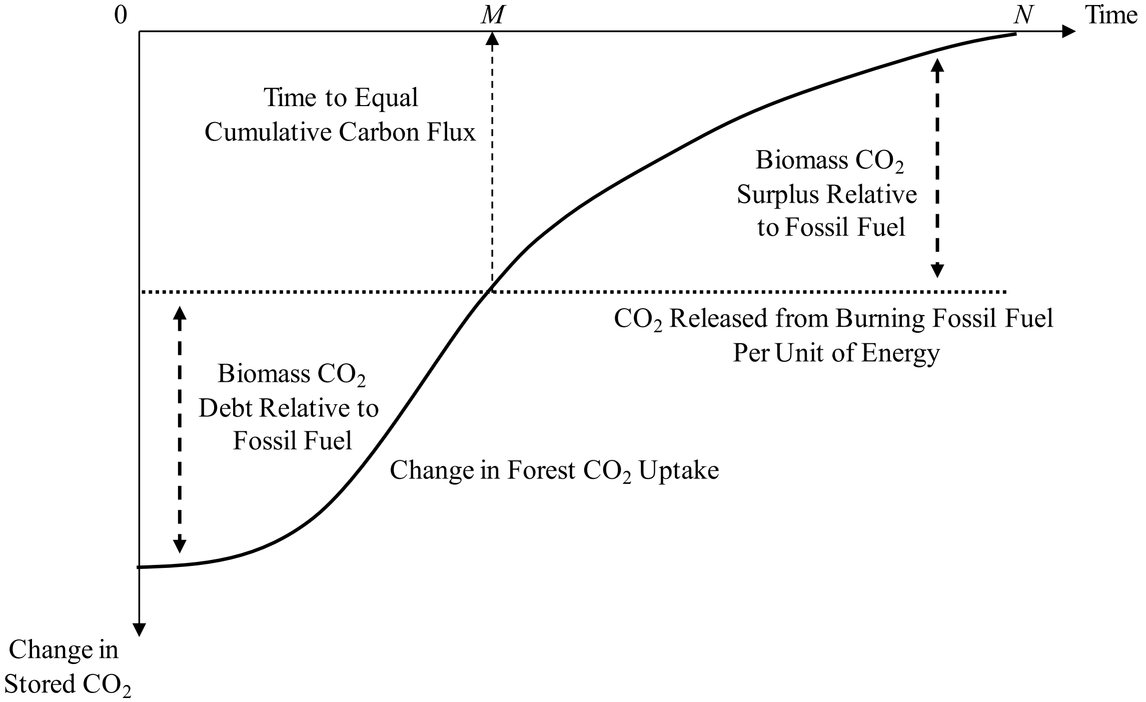


Figure 5.2: Carbon flux associated with fossil fuel and biomass energy production over time

The carbon neutrality of biomass is just as true for coal – only the time taken to subsequently remove the original emissions of CO_2 differs. Therefore, it is important to weight (discount) CO_2 uptake and release according to when it occurs. If global warming is not considered a problem, we might use a zero discount rate, in which case it really does not matter if biomass growth removes CO_2 from the atmosphere today, 50 years, or even thousands of years from now – it only matters that the CO_2 is eventually removed. In that case, coal and biomass are on a similar footing and, since coal is more energy efficient, it would be preferred to biomass.

If, on the other hand, global warming is considered the serious threat envisioned by the IPCC (2014) and NCA (2014), we want to weight current reductions in emissions and removals of CO_2 from the atmosphere much higher than those in future years. This is the same as discounting future uptake of CO_2, with higher discount rates suggesting greater urgency in dealing with global warming. Figure 5.3 depicts such urgency, but for a level of urgency where discount rates are sufficiently high that burning of biomass for energy never leads to carbon neutrality. Indeed, if one were to accept that climate change is a very urgent matter (a relatively high discount rate), substituting biomass for fossil fuels may actually lead to a net increase in atmospheric CO_2 emissions. In Figure 5.3, forest CO_2 uptake is discounted to such an extent that carbon uptake in the more distant future is of little value today. As a result, the discounted future uptake of carbon from the atmosphere is too small to offset the additional increase in CO_2 emissions when biomass substitutes for fossil fuels in power production.

The change in the cumulative carbon flux (measured in terms of CO_2) from substituting biomass for coal, say, will depend on the relative emissions intensity of the inputs, as well as the tree species or other plant type. Carbon dioxide released from burning coal and wood varies greatly by the quality of coal and type of biomass. In terms of energy efficiency, burning coal to generate electricity dominates burning of biomass, whether the biomass originates from hardwoods or softwoods. From Table 5.1, an average 0.518 tonnes (t) of coal are required to produce 1.0 MWh of electricity (assuming a heat rate of 10,498 and specified heat contents for various coal types as indicated). For the most commonly used bituminous coal, only 0.397 t of coal are required per MWh. Although wood species vary by density, all have a heat content of around 16.00 MMBtu t^{-1}. As a result, approximately 0.658 t of biomass are required to produce 1.0 MWh of electricity – nearly two times the amount required for bituminous coal. This can be translated into emissions intensities as indicated in Table 5.1. Thus, the average emissions intensity over all coal types is 1.015 $tCO_2\ MWh^{-1}$, compared to 1.170 $tCO_2\ MWh^{-1}$ for hardwoods and 1.242 $tCO_2\ MWh^{-1}$ for softwoods. However, since the majority of the world employs bituminous and subbituminous coal for power generation, with respective emissions intensities of 0.940 and 0.953 tCO_2 MWh^{-1}, biomass clearly releases significantly more CO_2 into the atmosphere per unit of energy than coal, and even more when compared to natural gas.

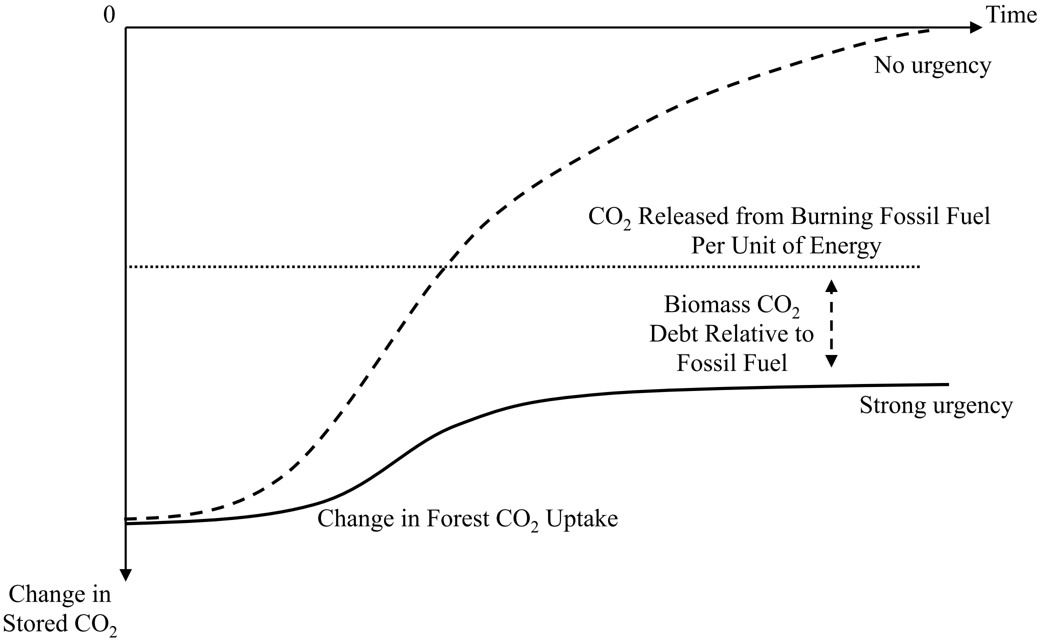


Figure 5.3: Carbon flux associated with fossil fuel and biomass energy production over time: greater urgency to address climate change

Accounting for carbon flux associated with bioenergy is further exacerbated by the fact that CO_2 emissions and uptake vary greatly by tree and plant species. To illustrate this point, consider the CO_2 intensities of lodgepole pine (*pinus contorta*) and white spruce (*picea engelmannii*), as indicated in Table 5.1. Both species emit approximately 1.24 tCO_2 MWh^{-1}, but they vary greatly in terms of their growth and stand dynamics, which affects the time profile of carbon sequestration. Thus, if CO_2 fluxes are weighted as to when they occur, this will impact the decision as to whether to employ biomass as a substitute for fossil fuels.

Table 5.1: Energy content and emissions parameters for select coal and biomass fuel types.

Input *Type*	Heat Content[a] (MMBtu/tonne)	C Content (%)	Density[b] (kg/m^3)	Fuel used[c] (t/MWh)	CO_2 Intensity[d] (t/MWh)	Fibre Required[e] (m^3/MWh)
Coal						
Anthracite	30.14	92.0%		0.349	1.177	
Bituminous	26.48	64.5%		0.397	0.940	
Lignite	13.25	34.0%		0.794	0.990	
Subbituminous	19.83	49.0%		0.531	0.953	
Average	22.43	59.9%		0.518	1.015	
Biomass						
Hardwood						
Hickory	15.99	48.5%	817	0.658	1.170	0.805
East. Hophombeam	15.99	48.5%	806	0.658	1.170	0.817
Apple	16.15	48.5%	782	0.652	1.159	0.834
White Oak	16.00	48.5%	758	0.658	1.169	0.868
Sugar Maple	15.96	48.5%	710	0.659	1.173	0.929
Red Oak	15.96	48.5%	710	0.659	1.173	0.929
Beech	15.96	48.5%	710	0.659	1.173	0.929
Yellow Birch	15.98	48.5%	697	0.658	1.171	0.945
White Ash	15.98	48.5%	697	0.658	1.171	0.945
Hackberry	16.00	48.5%	613	0.658	1.169	1.072
Tamarack	16.00	48.5%	613	0.658	1.169	1.072
Paper Birch	15.95	48.5%	600	0.660	1.173	1.099
Cherry	16.01	48.5%	589	0.657	1.169	1.116
Elm	15.96	48.5%	576	0.659	1.172	1.144
Black Ash	15.95	48.5%	565	0.660	1.173	1.168
Red Maple	15.98	48.5%	552	0.659	1.171	1.193
Boselder	15.99	48.5%	528	0.658	1.170	1.246
Average Hardwood	16.01	48.5%	666	0.658	1.170	1.006
Softwood						
Jack Pine	16.01	51.5%	504	0.657	1.241	1.304
Norway Pine	16.01	51.5%	504	0.657	1.241	1.304
Hemlock	16.01	51.5%	469	0.657	1.241	1.402
White Spruce	16.01	51.5%	466	0.657	1.241	1.412
Lodgepole Pine	15.96	51.5%	438	0.659	1.245	1.505
Aspen	16.04	51.5%	433	0.656	1.239	1.514
White Pine	15.98	51.5%	422	0.659	1.244	1.560
Balsam Fir	15.98	51.5%	422	0.659	1.244	1.560
Cottonwood	16.00	51.5%	398	0.658	1.242	1.652
Basswood	16.00	51.5%	398	0.658	1.242	1.652
Average Softwood	16.00	51.5%	445	0.658	1.242	1.486

Sources: EIA (2014), IEA (2013), IPCC(2006)

Notes: Carbon dioxide emissions are calculated from the carbon content of each fuel input using a factor of (44/12). That is the atomic weights of carbon dioxide over carbon.

[a] Based on 20% moisture content (M.C.) of biomass

[b] Air dry (20% M.C.)

[c] Calculated as (Heat Rate/Heat Content*1,000,000)*2,204.62. A heat rate of 10,498 btu/kWh is assumed (EIA, 2014)

[d] Calculated as (Fuel Used*C Content)*(44/12)

[e] Calculated as (Fuel Used/Density)*1,000

To highlight the significance of the carbon neutrality assumption, we illustrate how stand characteristics and growth functions affect estimates of CO_2 flux over time, and then how these are impacted by the perceived urgency to mitigate climate change. We find that one species may be preferred over another on the basis of its growth.

The data used in this chapter are for a one hectare (ha) plot, with stand characteristics consistent with those found in the Prince George forest region of British Columbia, Canada. A summary of stand characteristics for two tree species (lodgepole pine and white spruce) considered in this application are provided in Table 5.2. The BC Ministry of Forests, Lands and Natural Resource Operations' (Ministry of Forests and Range, 2010) Tipsy version 4.1 software is employed to project the tree basal area (TBA) of the two timber species. TBA is the cross-sectional area at breast height (BH = 1.3m above ground) used to estimate tree volumes and stand composition. Model input data for each yield table consisted of the species composition, regeneration delay, site index, operational adjustment factors (to account for gaps, endemic losses, waste, etc.) and initial density.

Table 5.2: Summary statistics of landscape and species

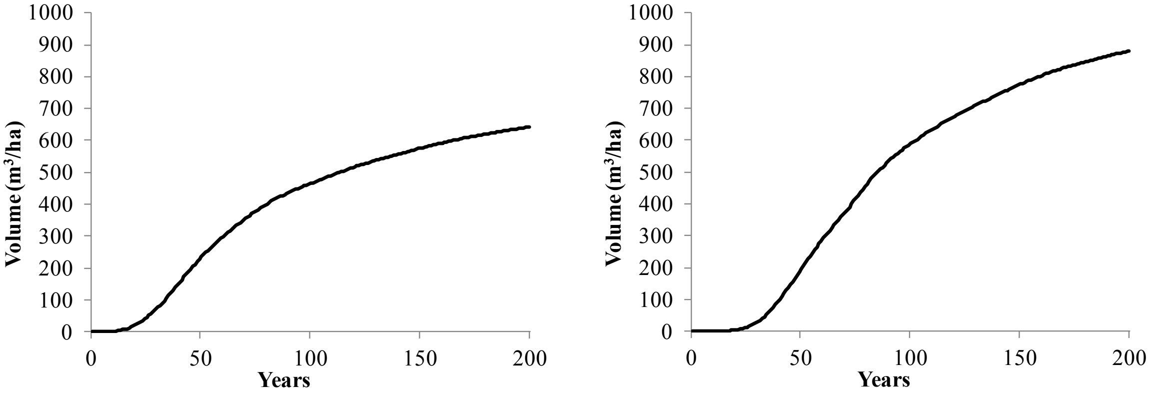
	Lodgepole pine	White spruce
Scientific Name	*pinus contorta*	*picea engelmannii*
Forest Region	Prince George	Prince George
Forest District	Dawson Creek	Dawson Creek
Biogeoclimatic Zone	BWBS	BWBS
Average Slope	10%	10%
Site Index	20	19.6
Stock Height (cm)	13	21
Initial Density	1,600	1,600
Curve	*Thrower (1994)*	*Goudie (1984)*
a	7.6298	9.7494
b	1.3563	1.4660
c	0.8940	1.2870

With the information from Table 5.2, Tipsy uses the following height-age (site index) curves for lodgepole pine and white spruce, respectively, to estimate growth:

$$H = 1.3 + (SI - 1.3)\frac{\left(1 + e^{\left(a - b\ln(50-0.5) - c\ln(SI-1.3)\right)}\right)}{\left(1 + e^{\left(a - b\ln(A-0.5) - c\ln(SI-1.3)\right)}\right)}, \tag{5.1}$$

$$H = 1.3 + (SI - 1.3)\frac{\left(1 + e^{\left(a - b\ln 50 - c\ln(SI-1.3)\right)}\right)}{\left(1 + e^{\left(a - b\ln A - c\ln(SI-1.3)\right)}\right)}, \tag{5.2}$$

where H is the average dominant height (m), SI is the site index (average BH at age 50 years), and A is the breast-height age (years). The projected volume (m^3 ha^{-1}) of lodgepole pine and white spruce in the Dawson Creek forest district of Prince George with an initial density of 1,600 trees ha^{-1} is provided in Figure 5.4.



(a) lodgepole pine (*pinus contorta*) (b) white spruce (*picea engelmannii*)

Figure 5.4: Projected volume (m^3 ha^{-1}) in Dawson Creek forest of Prince George district with average slope of 10% & initial density of 1,600 trees ha^{-1}

To estimate the amount of CO$_2$ removed from the atmosphere, the projected volume was adjusted using the following calculation:

$$CO2_t = \frac{V_t \times D \times \rho \times \frac{44}{12}}{1000}, \tag{5.3}$$

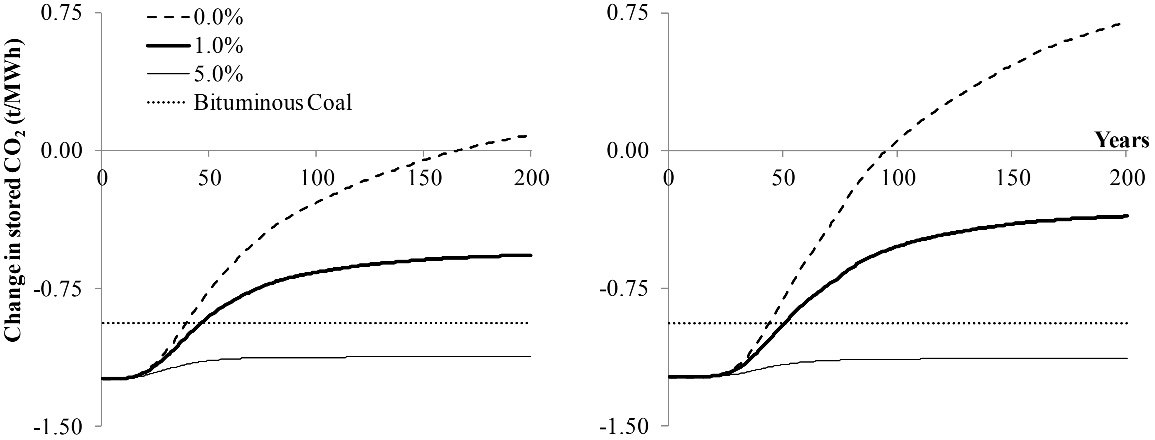
where *CO2$_t$* is the amount of CO$_2$ sequestered at time *t* (tCO$_2$ ha^{-1}), V_t is the volume at time *t* (m^3/ha) of the tree variety, *D* is the density of the tree variety (kg m^{-3}), ρ is the proportion of carbon by tree species, adjusted by the relative atomic weight of carbon dioxide over carbon, and finally adjusted to mass (tonnes). The total discounted CO$_2$ (*TDC*) removed from the atmosphere for these two tree species is calculated as a function of each annual increment of CO$_2$ sequestered, discounted as to when it occurs. Thus,

$$TDC = \sum_{t=1}^{T} \left(\frac{\left(CO2_t - CO2_{t-1}\right)}{\left(1+r\right)^t} \right), \tag{5.4}$$

where *r* is a weight (discount rate) on CO$_2$ uptake and release according to when it occurs. A higher value of *r* implies there is greater urgency to address climate change, and thus, less emphasis is attached to future CO$_2$ removals from the atmosphere.

5.3 Results

To calculate the change in stored CO_2 ($tCO_2\ MWh^{-1}$) over time, the discounted amount of CO_2 removed from the atmosphere is first adjusted to a per MWh basis and then added to the initial release of CO_2 from burning biomass (see Table 5.1). This calculation is presented in Figure 5.5 for lodgepole pine and white spruce across a selected range of discount rates. The release of CO_2 during energy production is assumed to occur at time $t = 0$, releasing 1.24 $tCO_2\ MWh^{-1}$ for lodgepole pine and white spruce, but only 0.94 $tCO_2\ MWh^{-1}$ for bituminous coal. The change in CO_2 storage associated with burning biomass for energy production is non-linear, as the initial emissions are offset by subsequent sequestration as trees grow, but discounted as to when this occurs. Again, the CO_2 cumulative flux associated with burning bituminous coal is indicated with a flat line as any subsequent carbon uptake or natural decay of CO_2 in the atmosphere is assumed to be negligible.



(a) lodgepole pine (*pinus contorta*)

(b) white spruce (*picea engelmannii*)

Figure 5.5: Projected cumulative carbon flux (tCO_2) associated with fossil fuel and biomass energy production for select climate change urgencies for two tree species

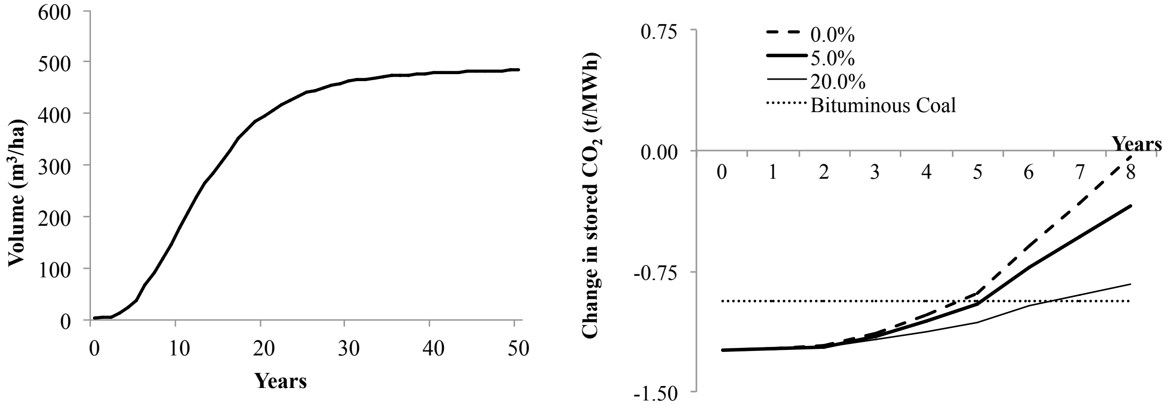
As evident from Figure 5.5, carbon neutrality occurs at different times in the future for the two species, but only for a 0% discount rate – that is, only if there is no urgency to address global warming. For lodgepole pine, it takes 166 years for the CO_2 released at the time of burning to be removed from the atmosphere by sequestration; in contrast, it takes only 95 years for emissions released when generating electricity from white spruce to become carbon neutral. The reason for this discrepancy is that white spruce grows faster and has a higher density than lodgepole pine. When there is greater urgency to prevent global warming so that current removals of CO_2 from the atmosphere are weighted more than future removals (which is equivalent to using higher rates to discount physical carbon), the date at which current CO_2 emissions are neutralized occurs much further in the future, if at all. Indeed, if climate change is deemed to be a quite urgent matter, biomass burning is never carbon neutral, regardless of the tree species used to offset emissions. In this application, a discount factor of 5 percent is assumed to represent urgency with respect to mitigating global warming, in which case subsequent sequestration of carbon by pine or spruce is insufficient to ever offset the initial carbon deficit associated with substituting biomass for coal. That is, the change in energy source from coal to biomass contributes more to increase atmospheric CO_2 as opposed to reducing it as desired by the renewable energy policies.

Hybrid Poplar

So far, we have shown that urgency to deal with climate change erodes the carbon uptake potential of lodgepole pine and white spruce, as these trees take decades to recover the CO_2 released by burning. Yet, many are turning to fast growing species within short-rotations to satisfy expansive bioenergy projects. In North America, many regions rely on hybrid poplar (*Populus spp.*) plantations to meet the growing demand for renewable energy sources, particularly in the Southeastern United States. Here, hybrid poplar is primarily derived from four species: black cottonwood (*Populus trichocarpa Torr. & Gray*), eastern cottonwood (*Populus deltoides Bartr. Ex Marsh*.), Japanese poplar (*Populus maximowiczii A. Henry*) and European black poplar (*Populus nigra L.*) (Stanton et al., 2002).

There are many challenges in examining how urgency to prevent global warming affects the CO_2 uptake potential of hybrid poplar plantations. Yields among similarly derived hybrid poplars may vary substantially (Laureysens et al., 2004), and in the particular case of the Southeastern United States, see Devineet al. (2010). As a result, maximum biomass productivity is expected with harvest cycles anywhere between three to eleven years (Sartori and Lal, 2006). As well, hybrid poplar yield is sensitive to variations in climate and soil characteristics (Truax et al., 2012).

In any event, certain assumptions must be established to simulate the carbon flux associated with biomass energy production from hybrid poplar. First, although harvest cycles may vary, it is assumed bioenergy purposed hybrid poplar follows an eight-year rotation cycle (Truax et al., 2012). Second, hybrid poplar is derived from varying species, with cottonwood being among the more commonly utilized. Thus, it is assumed that 1.65 m^3 of hybrid poplar is required to produce 1 MWh of energy, consistent with cottonwood in Table 5.1. With an assumed heat content of 16.0 MMBtu $tonne^{-1}$, density of 398 kg/m^3, and carbon content of 51.5%, the resulting emissions intensity of hybrid poplar is assumed to be 1.24 tCO_2 MWh^{-1}. Thirdly, although the estimated growth function will inevitably vary by the composition of hybrid poplar, it is assumed that growth follows a height-age (site index) curve consistent with equation (5.2), with site index of 50.1 m (average BH at age 50 years), $a = 8.926$, $b = 1.876$, and $c = 1.635$. The resulting estimated volume (m^3 ha^{-1}) of a hybrid plantation with similar site characteristics as outlined in Table 5.2 is provided in Figure 5.6(a).



(a) volume (m^3/ha)

(b) change in stored CO_2(t MWh^{-1})

Figure 5.6: Projected cumulative carbon flux associated with fossil fuel and biomass energy production for select climate change urgencies for two tree species

The discounted carbon flux from hybrid poplar is calculated consistent with equations (5.3) and (5.4) above, depicted in Figure 5.6(b). Here, the release of CO_2 during energy production is assumed to again occur at time $t = 0$, releasing 1.24 tCO_2 MWh^{-1} for hybrid poplar and only 0.94 tCO_2MWh^{-1} for bituminous coal. Thus, using hybrid poplar for energy purposes similarly relies on the fact that we count the future uptake of carbon as the plantation re-grows. Using a 0.0% discount rate (no climate change urgency), the hybrid poplar plantation returns to carbon neutrality on the eighth-year (its rotation cycle), resulting in an effective emissions intensity of 0.0 tCO_2 MWh^{-1}. However, if we place urgency on dealing with global warming the plantation fails to re-capture all the released CO_2 associated with energy production. For a rate of 5.0%, the effective emissions intensity is 0.35 tCO_2 MWh^{-1}, rather than 0.0 tCO_2 MWh^{-1} for a carbon neutral input. If we assumed great urgency in dealing with climate change and use a 20.0% rate, the effective emissions intensity is 0.83 tCO_2 MWh^{-1}, only slightly lower than 0.94 tCO_2 MWh^{-1} for bituminous coal. Thus, if global warming is deemed an urgent matter, coal may in fact be the preferred fuel input based on a lower effective emissions intensity as compared to bioenergy produced from a hybrid poplar plantation.

5.4 Summary and Discussion

The potential benefits of substituting biomass for coal to produce energy might be greatly exaggerated. Indeed, depending on the source of biomass and the perceived urgency to address climate change, using biomass to generate electricity might lead to greater warming rather than less.

Neglected in this research has been the CO_2 emissions related to harvesting, hauling and processing of timber into pellets, and shipping the pellets to the power plant. The same could be said about coal, although coal is mined at what essentially amounts to a single point on the landscape, and then loaded directly onto rail cars or hauled directly by truck to a power plant, usually with little or no further processing except crushing at the power plant. This contrasts with forest biomass that is harvested over a large landscape, with logs and sometimes roadside wastes trucked to processing facilities (see Niquidet et al., 2012); logs are processed into lumber and other valuable products, with residues from these processes made available for energy purposes. However, the process of converting fibre into wood pellets, torrefied pellets or charcoal for use in coal plants releases a significant amount of CO_2.

If we consider biomass from agricultural operations, the residues need to be gathered (harvested), transported and processed, and account needs to be taken of greenhouse gas emissions related to agrochemicals. The greenhouse gases emitted in the production, harvest and processing of energy crops often exceeds the reduction in emissions from replacing fossil fuels (Crutzen et al., 2008).

The production of timber or other energy crops increases land values (Ince et al., 2011, 2012; Moiseyev et al., 2011). This reduces land available for food production, which increases food prices thus harming the poorest in developing countries the most because they spend a greater proportion of their income on food. It also incentivizes the conversion of wetlands to cropland and natural forests to plantations, thereby reducing biodiversity and important ecological services provided by natural areas.

Finally, greater reliance on biomass for energy will increase the demand for wood residues, increasing their price in competition with wood manufacturers (who produce various industrial materials from wood residues) and pulp and paper producers (Stennes et al., 2010). This might make biomass too expensive to burn in power plants. Policies to promote biomass energy would then reduce economic activity in other wood using sectors (Raunikar et al., 2010), and increase electricity prices to the detriment of the least well off (Popp et al., 2011).

While electricity from biomass has merit in some cases, a nostalgic return to the past might also bring with it energy poverty, which many experienced in the past and an increasing number today. Misguided policies to increase reliance on wood biomass for energy yield little if anything in the way of reduced CO_2 emissions. Surely there must be more sensible alternatives for addressing climate change.

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Chapter 6

DISCUSSION AND CONCLUSION

This thesis presents four studies related to bioenergy product exports from forests. Although the individual studies stand on their own, their results share a common theme of examining economic issues surrounding a greater reliance on energy derived from forests. This section will highlight the main points of the studies, particularly their significance to policy. To conclude, this section will look to future work.

First, countries are aggressively pursuing renewable energy policies promoting bioenergy even though little is known about how it will impact the global forest products industry. Previous studies have concluded that increased bioenergy (fuelwood) demand results in a rise in forest product prices including sawnwood and panels (Raunikar et al., 2010; Buongiorno et al., 2011). From these conclusions, one could predict a multitude of economic welfare consequences, including a rise in housing costs. However, the focus on fuelwood is misplaced, as it is used primarily in developing countries for subsistence living (FAO, 2014). In contrast, the recent rise in bioenergy demand occurs mostly in developed countries, characterized by increased international trade in wood products; primarily met by residuals from downstream manufacturing, much of which is increasingly converted to wood pellets. By formulating the interaction between wood pellets and the sawmilling sector, it is shown that increased pellet demand may reduce the costs of processing logs, leading to increased output of lumber and, to a lesser extent, plywood and veneer. In fact, this relationship leads to a decline in the global price of sawnwood and panels where one could conclude increased bioenergy (wood pellet) demand may well lead to lower housing costs.

Secondly, countries in the European Union (EU) originally set a target of 20% renewable energy target by the year 2020, only to adopt a more ambitious target of 27% to be achieved by 2030 (European Commission, 2014). These policies are shown to disturb international wood product markets as countries within the EU further rely on biomass to meet their ambitious target of 27% renewable energy by 2030. The wood product market has emerged as an internationally connected market, where fibre is competitive distributed. Thus, policies promoting energy from biomass in one region may result in international ripple effects. With this in mind, it is shown that increased EU demand for wood pellets will be welfare enhancing to the global forest products industry, with the greatest gains coming from the consumers of wood pellets (i.e. energy producers). In the end, there will be winners and losers; timber rich regions with significant sawmilling capacity are estimated to be the major winners, while regions consuming particleboard, fibreboard, and pulp prove to be the greatest losers. Although the welfare impacts differ among regions and among wood product industries, the gains more than outweigh the losses, suggesting the possibility for the winners to compensate the losers.

Thirdly, an increase in the demand for wood pellets will inevitably lead to a rise in global pellet prices, raising concerns over their effectiveness as a renewable source of energy. As it stands, wood pellets cost more per unit of energy than many alternative fossil fuels, and thus require government support for their use. This is no more true than in Europe, where governments are setting aggressive renewable energy targets. To meet these targets, Europe will have to continue to rely on bioenergy, primarily characterized by wood pellet co-firing facilitated through increased imports. To the extent EU policies increase global pellet prices remains uncertain, although it will surely make alternative low CO_2–emitting sources like natural gas and nuclear more appealing.

This issue is further exacerbated as other regions of the world simultaneously implement their own policies that may encourage renewable energy sources like biomass. For example, the governments of Canada and the United States have adopted legislation that will see performance standards imposed on coal-fired power plants (see Canada Gazette, 2011 and EPA, 2013) where co-firing may be the most economical compliance strategy. As of 2014, there are already two large-scale coal-fired power plants in Canada retrofitted to run on wood pellets. The simultaneous implementation of renewable energy policies from around the world will inevitably put upward pressure on wood pellet prices, potentially encouraging other countries to pursue nature gas and nuclear to meet there energy needs.

Next, many countries are quick to adopt policies promoting bioenergy (e.g. EU member countries; Ontario, Canada) even though little is known about how these policies will impact the electrical generating grid. In particular, results of this dissertation suggest a few critical implications of using either a carbon tax, or a feed-in-tariff – two popular policies for encouraging renewable energy sources. For one, a carbon tax leads to lower CO_2-emitting sources at the expense of higher generating costs, as compared to a feed-in tariff on bioenergy. Secondly, a carbon tax may push the option to co-fire out in favour of low emitting fossil-fuel sources like natural gas.

Finally, all of the points made thus far may be irrelevant if energy produced from biomass is not deemed 'carbon neutral'. In an effort to reduce CO_2 emissions from fossil fuel burning, countries are investing in 'carbon neutral' biomass at increasing rates. Yet, biomass releases more CO_2 into the atmosphere per unit of energy than its fossil-fuel counterparts. Carbon neutrality of biomass hinges on the fact that we count each unit of atmospheric CO_2 removal equally, independent of when it occurs. With this in mind, it is shown the potential benefits of substituting biomass for coal to produce energy might be greatly exaggerated. When there is greater urgency to address climate change, less emphasis should be attached to future CO_2 removals from the atmosphere. The results of this chapter suggest that when the need to mitigate global warming is urgent, biomass may never return to carbon neutrality. Further, biomass combustion may be viewed as more CO_2-intensive than fossil fuels, if society places high enough urgency on dealing with global climate change. If one were to accept that global warming is an urgent matter, than the internationally accepted IPCC guidelines for carbon accounting are misplaced as we should weight future CO_2 removals less. Perhaps more importantly, as countries transition there energy grids towards biomass in lieu of the IPCC carbon accounting guidelines, society may be contributing more towards atmospheric CO_2.

The main points of this dissertation should be viewed in context of some potential uncertainties and assumptions. For one, although the primary source of data (FAO, 2012) may be less than desirable, it is used for its comprehensive coverage of the global forest products industry. Further, the global trade model of forests products omits hardwoods due to restrictions on data and that bioenergy trade is primarily characterized by softwood fibre (IEA Bioenergy Task 32, 2009). Future work may wish to expand upon the softwood model to include non-coniferous fibre; however the substitutability between species is difficult to model and may bring more uncertainty into the framework. Many scenarios used in this chapter assume an arbitrary rise in wood pellet demand resulting from renewable energy targets. Certainly, the projected effects on prices, consumption, production, and trade are sensitive to the exogenous shock, and more work is needed in forecasting the actual increase in wood pellet demand, particularly in the EU, Canada, and the United States. Other technical uncertainties include the use of fixed country-specific recovery factors employed in the global trade model. Creating endogenous factors (within reasonable bounds) would alleviate some of the rigidity in the model, facilitating greater choice. The global trade model would greatly benefit from the inclusion of dynamic considerations, and thus should be a main point of future work. Markets require time to respond, and the model may be more accurately applied to policy targets that are set at some future point. Lastly, the projections provided by this model should be compared to those provided by other global forest products trade models in order to shed more light on the significance of some of the new techniques used in this dissertation.

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APPENDIX

MODELLING BI-LATERAL FOREST PRODUCT TRADE FLOWS: EXPERIENCING VERTICAL AND HORIZONTAL CHAIN OPTIMIZATION

A.1 Introduction

Since the development of some of the earliest models of forest product trade, research has focused on expanding these models to consider more products in an international context. Utilizing gains in both computational and methodological proficiencies, models have become increasingly more complex, but there often remains confusion regarding the extent to which models are grounded in economic theory. Sometimes descriptions of forest trade models simply fail to provide a theoretical justification for their construction, thereby leading to lack of clarity about their projected welfare measures.

Modelling the global forest products sector is challenging for a number of reasons. Foremost, the forest products industry has emerged as an interconnected global market in which economic regions can best exploit their comparative advantages. Countries' domestic forest product sectors are inevitably linked via international markets. As a result, global trade in forest products reached US$ 224 billion in 2010, an inflation-adjusted increase of $62.5 billion over the previous decade.[25] Although numerical forest product models may be used to assess the

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[25] This figure represents the export value among all 159 countries represented in the FAOSTAT database across all forest products. Values are adjusted using the U.S. annual CPI index from the U.S. Bureau of Labor Statistics.

development of a domestic wood products processing sector, they must be viewed in the context of their connection to foreign markets.

Not only is the forest products industry connected through international trade, it is also comprised of many interconnected wood products. As wood fiber is generally sourced from the initial harvest of logs, the manufacturing of secondary wood products will not only be affected by the supply of logs, but also by competition for residual fiber. In fact, the initial demand for logs is derived from the demand functions for various manufactured wood products, including primarily lumber. Any structural shifts in the market for one of these products will inevitably impact the others.

The gains from trade in both logs and wood products result in increased economic welfare for both importers and exporters alike – even after adjusting for transportation costs. Forest policies that impact any one market, foreign or domestic, will impact other wood product markets, resulting in international welfare implications. Unraveling the complex effects in all domestic and international markets requires a model that is built upon a transparent economic framework. In this Appendix, we develop a vertically-integrated, 20-region bilateral trade model that relies on wood fiber from the harvest of timber as the primary input into various products that might be considered on a horizontal plane. We provide a theoretical background to the global forest trade model, a mathematical programming representation of the model, and a discussion of the data used in its construct and how it is calibrated.

We begin in the next section with a background analysis of the techniques used to analyze forest sector trade and its impacts, with particular emphasis on spatial price equilibrium models. This background information is used to justify the methods used here. We then derive our specific modelling framework, which considers the interactions between multiple markets in an integrated supply chain. Then, we outline the mathematical representation of the model, including the application of a precise calibration technique along with the underlying data. Conclusions and recommendations ensue.

A.2 Spatial Forest Product Models: Background

One approach for modelling spatially separated markets is based on econometrics. It has been applied to multiple issues, including forecasting forest product markets and prices, and industry location, as well as examining impacts of technological change. However, there are many problems associated with the econometric approach. For example, time-series forestry data often lack appealing econometric features, such as significant variation and stationarity, and are often collinear (Buongiorno, 1996). In fact, the use of econometric models may not necessarily be the most efficient way to study the development of the forest sector, as the sector is based on spatially separated markets with many products (Toppinen and Kuuluvainen, 2010). Rather, the greatest contribution of econometric methods might be their ability to provide quantitative information to be used in mathematical programming models. These models can be used for policy analysis and forecasting the future economic development of forest products and trade.

Another commonly used approach is the application of spatial price equilibrium (SPE), mathematical programming models. The SPE approach assumes that, while changes in countries' forest policies will affect prices of goods, they have no discernible impact on the relative prices of goods elsewhere in the economy. Spatial price equilibrium models are partial equilibrium trade models that assume any differences in prices between regions are the result of transaction costs, which include costs associated with transporting and handling goods (e.g., freight, insurance, exchange rate conversion fees), plus tariffs and other non-tariff barriers. It is assumed that, in the absence of trade barriers and transaction costs, prices of homogeneous goods would be the same in every region as a result of spatial arbitrage. One of the earliest formulations of equilibria among spatially separated markets is found in Enke (1951). Utilizing an electric analogue circuit, equilibrium prices and quantities are determined in a static model when three or more jurisdictions engage in the trade of a homogenous good. Spatial separation is made significant through freight costs per unit. Here, the electric circuit is compared to other methods of solution with other electronics. Enke's paper also highlights the important connection between a computable optimization model and traditional theory used commonly in determining optimal values in two-country trade situations.

Samuelson (1952) was the first to re-formulate Enke's approach into a mathematical linear programming trade model with spatially separated markets. He determined that Enke's complicated proposition could be arranged into a simpler style applying the theorem that the solution to a competitive equilibrium is identical to the maximization of social surplus, defined as the sum of the producer surplus and consumer surplus under perfectly competitive market conditions. In the trade situation, a unique equilibrium could be found by maximizing the total area between the excess demand and excess supply curve in each region, minus the total transportation costs of shipping goods between regions.

Takayama and Judge (1964, 1971) furthered the work of Enke and Samuelson on spatial equilibrium modelling to formulate the seminal quadratic programming problem used in most current mathematical trade models. Using linear regional demand and supply curves, the authors described the general solution for interregional prices and bilateral trade flows of multiproduct, *n*-region problems. We employ their approach to provide a general framework for solving interregional and international trade.

The approach is more commonly known as the Samuelson-Takayama-Judge (STJ) model (Samuelson, 1952; Takayama and Judge, 1971), whereby the objective is to maximize a quasi-welfare function (QWF) given as the difference of area below the demand and above the supply function, net of transaction costs. It can be stated as follows:

Maximize:

$$QWF = \sum_{j=1}^{R}\left(\alpha_j - \frac{1}{2}D_j x_j^D\right)x_j^D - \sum_{i=1}^{R}\left(b_j - \frac{1}{2}S_i x_i^S\right)x_i^S - \sum_{i=1}^{R}\sum_{j=1}^{R} t_{ij}x_{ij}\,, \tag{A.1}$$

Subject to: Dual Variable

$$x_j^D \le \sum_{i=1}^{R} x_{ij} \qquad\qquad p_j^D \tag{A.2}$$

$$\sum_{j=1}^{R} x_{ij} \ge x_i^S \qquad\qquad p_i^S \tag{A.3}$$

In this specification, there are *M* importing regions (denoted *j*) and *N* exporting regions (i). As the current model does not distinguish an importing region from an exporting region, there are *M*=*N* known inverse demand and inverse supply equations, written as $p_j^D = a_j - D_j x_j^D$ and $p_i^S = b_i + S_i x_i^S$ respectively. Coefficients a_j, D_j, b_i and S_i are known scalars, while demand and supply quantities, $x_j^D = \sum_{i=0}^{M} x_{ij}$ and $x_i^S = \sum_{j=1}^{N} x_{ij}$, with x_{ij} the amount of product *x* shipped from export region i to import region *j*. The x_{ij} unknown and must be endogenously determined. Finally, it is assumed that we have knowledge of the transaction costs of shipping a unit of x form i to j, t_{ij}.

The use of the spatial equilibrium concept in the forest products sector dates back to the early 1960s. Employing a spatial fibre allocation model, Holland and Judge (1963) studied the least cost strategy for transporting hardwood and softwood lumber to 11 demand regions from 18 supply regions within the United States. Holley (1970) used a similar approach to examine lumber and plywood demand, supply and trade in the United States. Holley included logging and manufacturing costs in the objective function to expand upon the work by Holland and Judge (1963). To study optimal location of industry, market shifts were exogenously implemented to provide projections from 1965 to 1975.

Building on the earlier works, Holley et al. (1975) created a linear program to model the least cost trade flows of 11 forest products in North America. Called the Inter-Regional Trade Model (ITM), timber availability and processing capacities offered constraints to the amount of products that could be consumed. The ITM's objective was to minimize the cost of supplying fibre for the projected increased demand scenarios.

By the late 1970s, the development of the spatial equilibrium modelling framework allowed for more explicit economic theory in trade modelling through developments in nonlinear programming techniques. The difference between this development and the spatial allocation models previously used can be summarized by two main improvements: first, regional supply and demand are expressed endogenously as functions, rather than pre-determined fixed values; second, the objective function is no longer one of minimizing costs subject to meeting some predetermined demand scenario, but rather it is to maximize the surplus value of trade, or the sum of all consumer and producer surpluses.

With this in mind, Haynes et al. (1978) were among the first to use the spatial equilibrium model to investigate the demand for forest products in the United States as a function of macroeconomic indicators (GNP, housing starts and population). Product prices were determined by substituting the equilibrium quantities consumed in each region into the regional demand functions.

The Timber Assessment Market Model (TAMM) developed by Adams and Haynes (1980) uses the spatial equilibrium modelling framework to provide long-range projections of consumption, production, price and product flows for softwood lumber, plywood and raw materials. Although the focus of the model is regional United States, it does include an international trade component, as Canada is included as a separate region. Demand and supply relations are determined using econometrics, and the model has a high degree of detail regarding production processes.

International trade modelling rapidly expanded in the 1980s with improvements in solution algorithms and computing capacities. Some of the first work on international trade of forest products includes Buongiorno and Gilles (1982). These authors rely on a spatial equilibrium model to analyze the global pulp and paper industry. Although the United States was again emphasized, the model incorporated Canada, Western Europe, Japan and the Rest of the World. The authors continued their efforts by developing a model of the North American pulp and paper industry, known as PAPYRUS (Gilles and Buongiorno, 1987). Long-term forecasts were developed for production, consumption, imports, exports, prices and fibre use. This linear programming model incorporated supply and demand curves for raw materials and final goods. In total, fourteen commodities are recognized in the model, with the United States and Canada represented by eleven supply and nine demand regions, and the rest of the world represented by three net demand regions.

Eventually PAPYRUS evolved into the Price-Endogenous Linear Programming System (PELPS-III) (Zhang et al., 1993), which was a system for modelling economic sectors. PELPS has a static stage and a dynamic phase. The solution to the static stage is based on the prices that clear multiple markets in a spatial equilibrium framework, and equivalent to the maximization of the sum of producer and consumer surpluses (again, referred to as the STJ framework and outlined by equations A.1, A.2 and A.3 above). The equilibrium found in the static phase is achieved simultaneously for several products, industries and regions. The dynamic phase of PELPS simulates the changes in the equilibrium values found in the static phase, but over a longer time horizon. In utilizing the PELPS model, the long-term forecast is revealed through the addition of multiple short-term equilibrium solutions (Buongiorno, 1996). In this way, the model allows for exogenous changes to the parameters, such as product demand changes as a result of changing demographics. Capacity is kept endogenous, even over the long term, as capacity is driven by the short-term equilibrium solutions. However, the model is not truly dynamically optimal as it lacks equations (with endogenous variables) that link one period to the next.

Subsequently, the Global Forest Products Model (GFPM) (Buongiorno et al., 2003) was built on the price-endogenous linear programming structure of PAPYRUS (Gilles and Buongiorno, 1987) and PELPS-III (Zhang et al., 1993). The GFPM is widely used in economic modelling of production, consumption and trade in forest products. It was developed as part of the United Nations Food and Agriculture Organization (FAO) work on forest sector outlook studies. The GFPM employs a price endogenous linear programming framework to model 180 countries and 14 products. Each country may produce, consume and trade each of the 14 products. In fact, the PELPS static/dynamic modelling framework is the structure for the GFPM. Timber supply, processing industries, product demand, and trade are modeled as annual static equilibriums, computed by maximizing social surplus. Year-by-year changes are simulated in a dynamic phase, whereby static phases are linked together to construct the dynamic simulations. As the GFPM relies on the PELPS modelling framework, they are fundamentally similar.

To allow for the complexity of a global trade model with multiple products, the GFPM is constructed from one world model and four regional sub-models (Africa, America, Asia and Europe). These four regional sub-models are constructed with area specific detail, with additional constraints ensuring that aggregate trade flows are consistent with those predicted by the more general world model. Thus, the world model must be solved first to predict consumption, production, prices and trade. Regional models export and import to a hypothetical world region in order to satisfy aggregate demand and supply conditions. Although this simplification allows for the added complexity of multiple products in a global market, it does so at the cost of a transparent, bilateral trade flow analysis.

A.3 Partial Equilibrium Trade Modelling: Theory

To illustrate the development of the forest product trade model, consider Figures A.1 and A.2. In the figures, lumber trade is assumed to occur between two countries. The effects of trade can be understood by analyzing excess supply and excess demand functions. A diagrammatic explanation of spatial price equilibrium trade models, and excess supply (ES) and excess demand (ED) functions, can be found in Just et al. (2004), Schmitz et al. (2010) and, in the context of forestry, van Kooten and Folmer (2004, pp. 409-421).

Autarky and the Excess Supply and Demand Functions

In Figure A.1, the domestic supply of lumber is *S* and the demand is *D*. The equilibrium price and quantity for lumber in autarky are p_1 and q_1, respectively. Suppose the price rises above p_1 for whatever reason (e.g., trade). If it were to rise to p_2, the country will produce q_2 but only consume q_3. In other words, the country will supply $q_2 - q_3$ more lumber than it would consume at the given price p_2. The quantity available for export for any price above the autarky price of p_1 is given by the horizontal difference between the quantity supplied and the quantity demanded for a given price. This is how the ES curve is derived. For example, at the price p_2, the excess supply of lumber is q_4, which is exactly equal to $q_2 - q_3$. The area above the ES curve below a given price is a measure of the gains from trade. This gain equals area *a*, which is exactly equal to area *b*, and is the excess of producer surplus gain over the consumer surplus loss as a result of moving from the autarky equilibrium price p_1 to p_2.

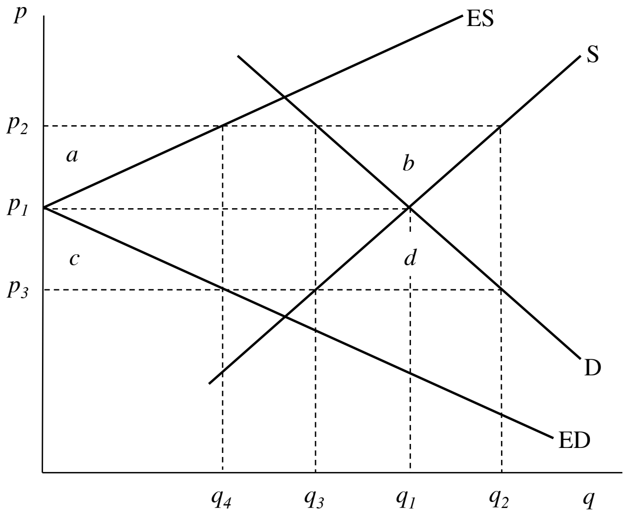


Figure A.1: Excess Supply and Excess Demand

Similarly, the excess demand curve is represented in Figure A.1 by price deviations below the autarkic price. Suppose, as the result of free trade, price falls from p_1 to p_3. Consumers desire quantity q_2 while producers only supply q_3, so imports of lumber of amount $q_2 - q_3$ occur. The excess demand schedule ED is derived by horizontally subtracting quantities supplied along the supply curve from quantities demanded along the demand curve. For example, if the price were to fall below p_1 to p_3, the country would import q_4, which is exactly equal to $q_2 - q_3$. The area below the ED curve bounded by a given price is a measure of the gains from trade. This area equals *d* (equals area *c*), which is the excess of consumer surplus gain over the producer surplus loss as a result of moving from the autarky equilibrium price p_1 to p_3.

The ES and ED schedules can be derived mathematically. Suppose the (inverse) demand and supply curves in Figure A.1 are linear:

$$P^D = \alpha - \beta q,\ \alpha, \beta \geq 0, \text{ and} \tag{A.4}$$

$$P^S = a + bq,\ a, b \geq 0. \tag{A.5}$$

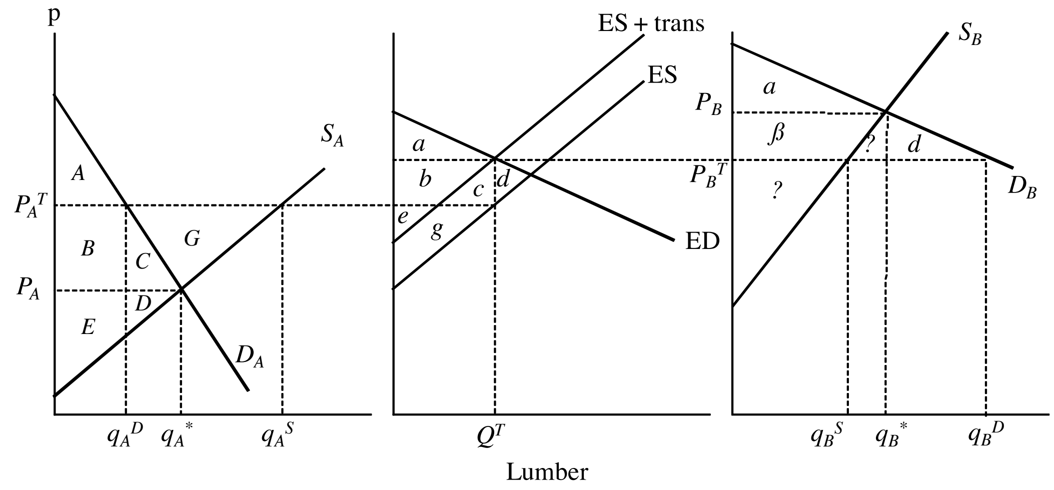
The excess demand and supply curves in the figure are then given by:

$$ED = \gamma - \delta q, \text{ with } \gamma = \frac{a\beta + b\alpha}{\beta + b} \geq 0 \text{ and } \delta = \frac{b\beta}{\beta + b} \geq 0. \tag{A.6}$$

$$ES = \gamma + mq, \text{ with } \gamma = \frac{a\beta + b\alpha}{\beta + b} \geq 0 \text{ and } m = \frac{b\beta}{\beta + b} \geq 0. \tag{A.7}$$

Notice that γ is the equilibrium domestic price in autarky, such that in the absence of shipping and handling costs, the excess supply and demand curves start at the same point on the vertical (price) axis. Further, the absolute slopes of the ED and ES curves are identical, although ED slopes down and ES slopes up.

For grammatical convenience, consider first lumber trade between only two countries or regions, A and B. The two-country example offers an excellent way to illustrate how spatial price equilibrium trade models can be used to analyze policy. A numerical mathematical programming model would be required to model the real world as it is characterized by bilateral trade among many countries or regions. The two-country spatial price equilibrium lumber trade model is illustrated in Figure A.2.



(a) Country A (b) International Market (c) Country B

Figure A.2: Model of Trade in Lumber

In the figure, the domestic demand functions in countries A and B are given by D_A and D_B, respectively, while the domestic supply functions for lumber are given by S_A and S_B. Under autarky, an amount q_A* will be supplied and consumed in country A, at a domestic price of P_A (see Fig A.2a); in country B, the autarkic price and quantity are P_B and q_B* (Fig A.2c). Note that, for trade to take place, the difference between autarkic prices must exceed the cost of transporting the good from one market to the other; that is, $|P_A - P_B| > t$, where t refers to the shipping, handling and other costs.

Economic wellbeing or welfare is always determined as the sum of surpluses (van Kooten 2014; Just et al. 2004); that is, the wellbeing of citizens in each country is determined by the sum of the benefits they receive as consumers (consumer surplus) and as producers (producer surplus or quasi-rent), plus any surplus that can be attributed to the country's natural resources. In the absence of trade, the consumer surplus associated with the lumber market is given by area ($A + B + C$) in Figure A.2(a) for country A, and area α in Figure A.2(c) for country B. The producer surplus in the absence of trade is measured by area ($E + D$) for country A and ($\gamma + \beta$) for country B. Total economic wellbeing is the sum of producer and consumer surpluses, and is simply given by the area between the demand and supply curves. For country B, total surplus in the absence of trade is given by area ($\alpha + \gamma + \beta$), while it is ($A + B + C + D + E$) for country A.

Gains from Trade

To demonstrate that trade improves the wellbeing of both countries, it is necessary to show that the total surplus in each region increases as a result of trade. In the absence of trade, the price in country B exceeds that in country A (Fig A.2). With trade, the price in country B falls from P_B to P_B^T, while country A's price rises from P_A to P_A^T. Consumers in country B gain as a result of the price decrease; consumption rises from q_B* to q_B^D and consumer surplus increases from area α to area (α+β+ϕ+δ). However, producers in country B face a lower price, namely, $P_B^T<P_B$ in panel (c), causing them to reduce production from q_B* to q_B^S. An amount $q_B^D–q_B^S$ is purchased from country A, while producer surplus falls from (γ+β) to just γ. The overall wellbeing of country B increases by area (ϕ+δ), with consumers (home builders, furniture makers, etc.) as the main beneficiaries of trade.

The situation in country A mirrors that of B. The rise in country A prices causes consumers to purchase less lumber (from q_A* to q_A^D) and reduces their overall consumer surplus by area (*B*+*C*). Producers in country A now receive a higher price and ramp up their production of lumber from q_A^* to q_A^S, leading to an increase in producer surplus of (*B*+*C*+G) in the process. The wellbeing of country A as a whole increases by area *G*, with producers (manufacturers of lumber) the main beneficiaries from trade.

The main results can be summarized in the international market, Figure A.2(b). The amount traded between A and B is $Q^T = q_A^S–q_A^D = q_B^D - q_B^S$. The net gain to country B is area *a*, which is equal to area (ϕ+δ) in panel (c); the net gain accrues to consumers in country B, and is therefore measured under the excess demand curve. Meanwhile, the net gain to country A is the area (*e*+*g*), which is equal to area *G* in panel (a); this gain accrues to the producers of lumber. Note that shipping and handling costs equal to (*b*+*c*) can also be identified in Figure A.2(b).

A.4 Vertically and Horizontally Integrated Forest Sector

In the preceding discussion, the impacts of changes in the lumber market on vertically- and horizontally-related markets were ignored. In many situations this is not realistic. As an illustration, suppose the government imposes a quota on softwood log exports. Although this will inevitably impact local industrial roundwood prices (reducing them) and thus profits earned by forest landowners, some of the reduced cost will be passed down the marketing chain to processors of logs and, ultimately, consumers of wood products such as lumber, plywood, pulp, et cetera. The reduced price of wood fiber can lead to lower lumber prices that, through competition, could be passed along to home builders, furniture makers and so on. However, the linkages could be complex, but they should be considered when evaluating the impact of any policy affecting the forest products industry.

In this section, we aim to establish a framework for evaluating the welfare effects of price changes in vertically-related markets. The analysis begins by considering a marketing chain for logs used in the production of lumber, ultimately consumed by construction, furniture and other lumber users. Then, in the next section, the analysis is extended to consider multiple users of logs – not just lumber, but producers of plywood, oriented strand board (OSB), medium-density fiber board (MDF), pulp, wood pellets, and others. The fiber from the initial harvest of logs is competitively distributed to multiple processors through horizontally integrated markets. These complex vertical and horizontal relationships suggest a framework for establishing a global trade model of forest products that is rooted in economic theory.

Vertical Chain Integration

To motivate the discussion of the underlying theory and assumptions that enable the integration of vertically connected markets in a trade model, consider the vertically-integrated sectors depicted in Figures A.3 and A.4. In Figure A.3, we are concerned with the derivation of a competitive supply curve for lumber that takes into account the equilibrium adjustments to the input price of logs. With the competitive supply curve in place, we then isolate the welfare consequences of price changes in the vertically-related markets depicted in Figure A.4.

As a matter of clarity, we refer to two types of supply and demand curves. An *intermediate* supply or demand curve refers to a relation between price and quantity that does not take into account the effect of changes in the prices of the commodity in question on *related* goods or services. Rather, it does not take into account the rebound effect that the policies in one market have on the prices in related markets that, in turn, affect the demand or supply in the original market. The *general equilibrium* supply and demand function takes these rebound effects into account, as discussed in the next paragraphs. It is appropriate to measure the consumer and producer surpluses as areas under the general equilibrium demand and supply curves, respectively (Just et al. 2004).

To derive the competitive supply curve for lumber that accounts for input prices (denoted with r), consider a competitive lumber industry that uses logs as inputs (Fig A.3). The log market is assumed to have a perfectly elastic supply for inputs (fixed input prices);[26] that is, fluctuations in inputs used to produce logs are assumed not to affect the prices of logging equipment, trucks, fuel, workers, et cetera. However, the lumber market depicted in Figure A.3(b) is characterized by an upward sloping, intermediate supply curve $S_{lum}(r^0{}_{log})$, and an initial input price of $r^0{}_{log}$ and output price of $P^0{}_{lum}$. The demand for logs in Figure A.3(a) is derived from the downstream manufacturers of lumber, as logs are the single most important input into the production of lumber – the demand for logs by lumber producers is given by the value of the marginal product of logs in the production of lumber, or the marginal physical product of logs in the production of lumber multiplied by the output price of lumber. Given a derived demand of $D_{log}(P^0{}_{lum})$, the log market has initial price $r^0{}_{log}$ along its intermediate supply curve S_{log}.

Suppose the output price in the lumber market falls to $p^1{}_{lum}$ as the result of policy intervention. Initially, manufacturers of lumber adjust their production to $q^2{}_{lum}$ along their initial intermediate supply curve, as they do not perceive the effects of their decisions on the (related) log market. As a result of the price change in the lumber market, the derived demand for logs falls to $D_{log}(P^1{}_{lum})$, thereby reducing the price of logs to $r^1{}_{log}$. In turn, the lower input price leads to a downward shift from $S_{lum}(r^0{}_{log})$ to $S_{lum}(r^1{}_{log})$ in the intermediate supply curve for lumber, giving rise to new equilibrium output and price combination of $q^1{}_{lum}$ and $P^1{}_{lum}$. One can then derive a general equilibrium supply curve for lumber (denoted $S^*{}_{lum}$) by connecting the original and final equilibriums; the general equilibrium supply function allows for equilibrium adjustments of input use and input price, as output price changes. In Figure A.3, $S^*{}_{lum}$ differs from the intermediate supply curve, say $S_{lum}(r^0{}_{log})$, as the latter only indicates how the lumber market will respond to price fluctuations under the premise that input prices are fixed.

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[26] We use r to denote input prices and P to denote prices in downstream markets. Thus, r is used in the case of logs and markets upstream of logs, and P for lumber and markets downstream.

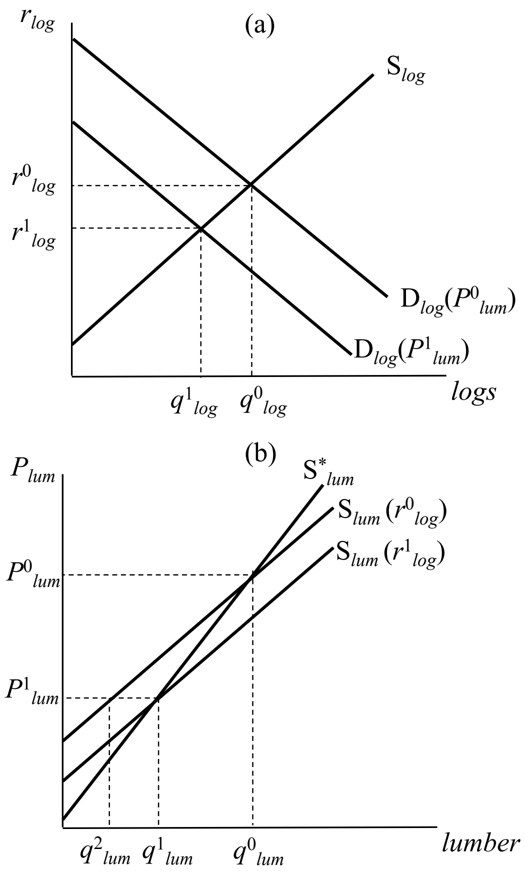

Figure A.3: Derivation of the general equilibrium competitive supply curve for lumber in a vertically integrated market chain

To see how one can measure the welfare implications of policy intervention in multiple vertically connected markets, consider Figure A.4. Following van Kooten (2013), it is shown that three types of economic surpluses must be considered: (1) consumer surplus, (2) quasi-rent (producer surplus), and (3) the rent created as a result of policy induced scarcity. It is assumed that the input supply schedule S_{n-1} facing market n-1 (the logging sector) is perfectly elastic so that input prices r_{n-1} (logging equipment, trucks, fuel, labor, etc.) are not affected by changes in the demand for such inputs as a result in changes in log output. It is assumed that all of the logs produced by the logging sector are inputs into lumber production (panel c). Lumber is an input into downstream industries such as (primarily) construction, furniture making and other activities, where it is assumed that the demand in this market is perfectly elastic, D_{n+1}. That is, changes in lumber prices do not affect the prices of houses, buildings, furniture, and so on, because lumber is either too insignificant an input or can readily be substituted by other products. The general equilibrium lumber supply curve S^*_{lum} allows for equilibrium adjustments of input use and input price as output price changes (as discussed above). Finally, to make the following analytical discussion tractable, it is assumed there are no other wood products using logs as inputs – no markets are horizontal to lumber in Figure A.4(c). This assumption will be relaxed later in the discussion of horizontal market integration.

Suppose a quota of q^1_{lum} (or an equivalent ad valorem tax) is imposed on the producers of lumber. As a result of reduced lumber production, the price consumers of lumber (construction, furniture making and other users of lumber) must pay rises to P^1_{lum}, while the price lumber producers receive falls to P^2_{lum}. Since the demand curve for lumber is derived from the demand for these downstream products, the reduction in consumer surplus, as given by area (a+b) in panel (c), is equal to the change in quasi-rent in the market for downstream users of lumber. Thus, it is necessary to measure only one of these changes, say area (a+b) in panel (c), and not the equivalent loss of area (α+β) in the downstream market for users of lumber in panel (d).

Now consider the change in consumer surplus in the log market in panel (b). As a result of the government policy that reduced the production of lumber from q^0_{lum} to q^1_{lum} in panel (c), derived demand for logs shifts downward from $D_{log}(P^0_{lum})$ to $D_{log}(P^2_{lum})$. Due to this lower demand for logs, the price falls from r^0_{log} to r^1_{log}, causing a change in consumer surplus equal to (u–y). Since it is assumed that all logs are used in the production of lumber, the change in consumer surplus in the log market is equal to the change in quasi-rent in the downstream lumber market. Thus, the change in consumer surplus in the log market equals the loss (c+d) in Figure A.4(c). Notice that the general equilibrium, competitive supply curve for lumber S^*_{lum} takes into consideration the effect of the new log price, P^1_{log}, on lumber supply; thus, it is not necessary to have S^*_{lum} shift as a result of this price change as it is inherently incorporated through its derivation (as discussed in conjunction with Fig A.3).

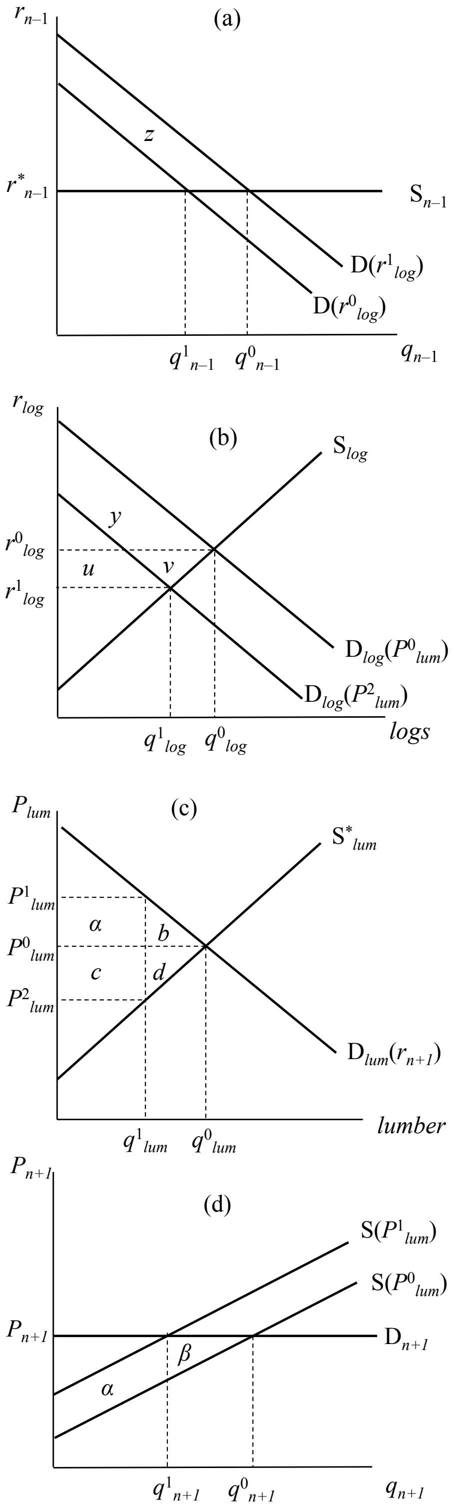

Figure A.4: Vertically integrated log and lumber markets

There remain two additional surplus measures that need to be taken into account. First, in the log market (Fig A.4b), the loss in quasi-rent to log producers is equal to area (*u*+*v*), which is equivalent to the change in consumer surplus of area *z* in the upstream market for logging equipment, trucks, fuel, labour, et cetera (Fig A.4a). Again, this area must only be measured once, say in the log market, and not the equivalent measure in the upstream market.

Finally, in the lumber market (Fig A.4c), a scarcity rent is created equal to area (*a*+c), as supply is constrained to be lower than demand as the result of policy intervention. Producers of lumber may capture the scarcity rent if it were created through a quota on production, while if it arose due to an ad valorem tax the government captures it as tax revenue.

The point of the above analysis is this: the welfare measures appropriate for a vertically integrated forest trade model are the consumer surplus, producer surplus (quasi-rent) and scarcity rent. This result hinges on the assumption that remaining upstream and downstream markets are characterized by perfectly elastic output demand and input supply, respectively. It is also predicated on the assumption that other wood product markets (horizontal markets to lumber) are characterized by a perfectly elastic demand function or that lumber production is the only downstream use of logs. We now consider what happens if this is not the case.

Horizontal Chain Integration

So far we have considered the vertical relationship between one input and one output, with additional upstream and downstream markets considered as having respective infinitely-elastic supply (fixed input prices) and demand (fixed output prices). Now consider a vertical chain such as that discussed above, but with several outputs from logs and not just lumber; that is, we consider multiple products that use wood fiber from the harvests of timber. The addition of these other wood product markets horizontal to lumber in the marketing chain adds complexity, but also greater reality, to the model. Although lumber remains the primary use of logs, other wood products, such as plywood, oriented strand board (OSB), particleboard, which includes wafer board, strand board and medium-density fiberboard (MDF), wood pulp, wood pellets, and wood wastes and residuals continue to be a significant part of the global forest products industry.

To add to the challenge of integrating horizontal markets into the discussion, logs are not only an input to downstream processors, but fiber may also flow between two or more horizontal markets. For example, the markets for lumber and wood pellets are on the same horizontal market segment (i.e., downstream of logs in the vertical supply chain), because both utilize fiber that originates with the initial log harvest. However, the lumber manufacture produces, among other things, sawmilling residuals that are commonly used in the production of most other wood products, including wood pellets. Wood pellets and lumber are *complements* in production in the sense that by-products from lumber manufacture are used to produce pellets. The more lumber that is produced, the more fiber becomes available to produce wood pellets. Alternatively, two products may be *substitutes* in production if they compete for the same input. Lumber and plywood manufacturers compete for the same industrial roundwood, with logs used to produce lumber (plywood) not available to produce plywood (lumber). Some products are both complements and substitutes in production. For example, pulp chips are residual to lumber and plywood production, but whole logs can be chipped and used solely to produce pulp. This is true, just as well, for wood chips, OSB and some other products.[27] In practice, the value of logs in lumber is generally much higher than in other uses so that harvests might not even take place unless the roundwood logs are designated to be processed into lumber. Exceptions occur where plantations of fast-growing species such as hybrid poplar have been established to service a biomass power plant or pulp mill.

To demonstrate the importance of the distinction between complements and substitutes in production, consider the expansion of the vertically integrated market structure given in the Figure 4. Here we have K markets horizontal to lumber, differentiated according to whether they are primarily complements or substitutes to the production of lumber. Let i (= 1, …, k) denote wood products that are joint products (complements) in the production of lumber or plywood, and j (= k+1, …, K) denote wood products that are competitive in (substitutes to) the production of lumber. Further, let $S_i^*(P_i; P_{i\text{-}}, P_j, P_{lum})$ and $S_j^*(P_j; P_{j\text{-}}, P_i, P_{lum})$ be the respective supply curves for complements and substitutes that incorporate equilibrium adjustments of log inputs and their prices (as indicated by the asterisk), and $P_{i\text{-}}$ and $P_{j\text{-}}$ denote prices of joint and competitive products, respectively, other than that of the product under consideration. The equilibrium supply

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[27] One caveat should be noted. Some logs are not suited to the production of lumber or plywood and might only be worth chipping for pulp purposes or used as a biomass fuel.

functions do shift, however, with changes in the prices of horizontal products.

A change in the price of lumber will lead to changes in relative prices across *h* horizontal markets. If markets are competitive, an increase in the price of lumber will lead to greater use of fiber in lumber production – (1) logs will be cut more efficiently to produce more lumber, (2) logs will be competed away from other log processors (e.g., plywood manufacturers), and/or (3) harvests of commercial roundwood logs will increase. In the first case, the supply of fiber available to complementary products, such wood pellets and pulp, will decline. In the second case, it is not clear if the amount of residual fiber from plywood manufacture, for example, is more or less than with lumber manufacture. Consider the third case. In modern sawmills, computers are used to obtain the greatest value from logs. In that case, although there will be some shifting of fiber from plywood to lumber, say, it will generally be possible to increase lumber production only by increasing harvests. Thus, the amount of fiber available to complementary horizontal markets will increase. Overall, however, it is unclear as to the effect that an increase in the price of lumber will have on the supply of complementary products:

$$\frac{\partial S_i^*\left(P_i;P_{i-},P_j,P_{lum}\right)}{\partial P_{lum}} \mathrel{\substack{<\\>}} 0, \quad \forall\, i = 1, \ldots, k. \tag{A.8}$$

On the other hand, in markets for products that are substitutes in production with lumber, an increase in the price of lumber will reduce fiber available for those products and thus reduce their supply:

$$\frac{\partial S_j^*\left(P_j;P_{j-},P_i,P_{lum}\right)}{\partial P_{lum}} < 0, \quad \forall\, j = k+1, \ldots, K. \tag{A.9}$$

One can measure the welfare implications of policy intervention in multiple vertically and horizontally connected markets. Building upon the framework established above, in Figure A.5 we add horizontal markets *i* and *j* to the horizontal market segment for lumber in the vertical chain – a market *i* is added to the left of lumber and a market *j* to the right. Again we assume that, in the $(n–1)^{\text{th}}$-level markets upstream from logs, the supply functions are perfectly elastic. This implies that the prices of inputs into the production of logs do not change with changes in the harvests of logs. Likewise, we assume that changes in the supplies of the *K* outputs produced from wood fiber, whether lumber, plywood, OSB, wood pellets, et cetera, do not change the prices in the $(n+1)^{th}$-level downstream markets in the vertical chain – the demand functions in these markets are perfectly elastic. For example, as the global supply of wood pellets changes, the prices received for electricity in various countries are not impacted. Likewise, as the supplies of lumber and/or plywood change, the prices of residential construction or furniture do not change. Therefore, we ignore these upstream and downstream markets in the discussion of Figure A.5.

Now consider the vertically and horizontally integrated forest sectors depicted in Figure A.5. Logs are the main input into the processing of forest products. It is assumed that the supply functions of any other inputs into forest products manufacturing are perfectly elastic; thus, increases in the demand for labor, machinery, fuel and so on by the processing sector does not affect the prices of these inputs. As noted above, lumber is considered the most important product from the processing of logs. Then, in Figure A.5, there exist two markets horizontal to lumber in the supply chain: market j whose output is considered competitive for fiber in the production of lumber (a substitute), and market i whose output is considered a joint product with lumber (complement); that is, product j competes with lumber for logs, while product i can utilize material directly from logs but relies primarily on residuals from the manufacture of lumber and the manufacture of other wood products j. The supply curves for the two markets are assumed to behave in a manner consistent with equations (A.8) and (A.9); however, in the discussion pertaining to Figure A.5, we simply assume that the supply function for complements in production, i, will shift outwards (increase) with an increase in the price of lumber, so the sign in equation (A.8) is positive. Finally, the demand for logs $D_{log}(P_i, P_j, P_{lum})$ is assumed to be derived from the demands by downstream wood fiber processors.

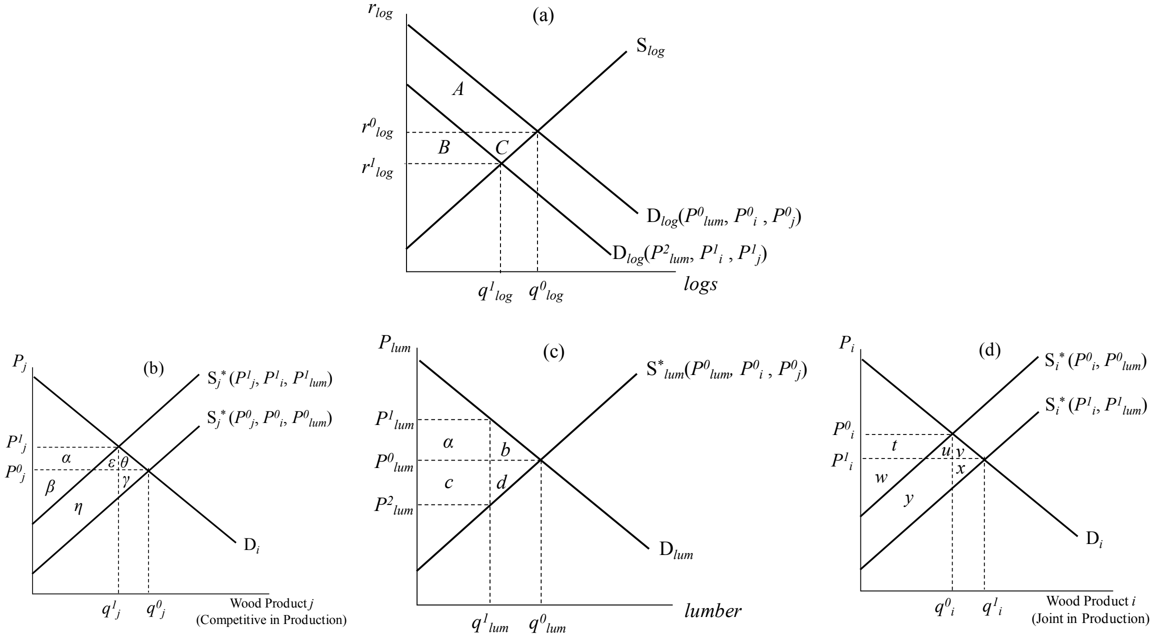

Figure A.5: Vertically and horizontally integrated wood product markets

Suppose lumber output is somehow constrained to q^1_{lum} as a result of a quota or a per unit tax ($=P^1_{lum} - P^2_{lum}$). As a result, the marginal cost of producing lumber falls from P^0_{lum} to P^2_{lum} in Figure A.5(c), although in the case of a quota lumber producers may actually receive P^2_{lum} or the demand price P^1_{lum} depending on which entity is able to collect the policy-created scarcity rent. Nonetheless, the higher demand price of lumber affects markets that are horizontal to lumber in the supply chain as indicated in panels (b) and (d).

First consider the market for substitutes in production in Figure A.5(b). The lower willingness to pay for logs by lumber producers will result in less fiber directed towards lumber (as fiber is competitively distributed), allowing for additional resources used in producing *i* substitute products. Consistent with equation (A.8), this effect is represented as a rightward shift in the supply curve from $S_i^*(P^0_i; P^0_{i\text{-}}, P^0_j, P^0_{lum})$ to $S_i^*(P^1_i; P^1_{i\text{-}}, P^1_j, P^1_{lum})$, giving rise to a new price and quantity combination P^1_i and q^1_i.

Meanwhile, the fall in lumber production from q^0_{lum} to q^1_{lum} results in fewer by-products (i.e., chips and residuals) available to markets (*j*), whose production is complementary to lumber. That is, production in the *j* market uses residuals from lumber manufacturing as inputs. Consistent with equation (A.9), this effect is represented through an upward shift in the supply curve of j markets from $S_j^*(P^0_j; P^0_{j\text{-}}, P^0_i, P^0_{lum})$ to $S_j^*(P^0_j; P^0_{j\text{-}}, P^0_i, P^0_{lum})$, giving rise to new price and quantity combination P^1_j and q^1_j. It is important to recall that the supply curves for all downstream markets from logs are denoted with an asterisk (*), as they incorporate equilibrium adjustments to input (log) prices. That is, further consideration of the impact of the price of logs on downstream users need not be represented diagrammatically in Figure A.5.

The demand for logs $D_{log}(P_{lum}, P_i, P_j)$ is derived from the demand for downstream wood processors. It will inevitably be affected through the price changes in the markets for lumber, substitutes i and complements j. As a result of the policy intervention in the lumber market, the derived demand for logs shifts down to $D_{log}(P^2_{lum}, P^1_i, P^1_j)$ giving rise to new price and quantity combination of r^1_{log} and q^1_{log}. This price change for logs is reflected in the downstream supply curves, as they incorporate equilibrium adjustments of input prices.

Before proceeding, it is important to take note of two important points that hinge on the fact that the lumber market is the primary processing sector. First, although prices change in all downstream markets, it is assumed that any shifts in the derived demand for logs will ultimately be driven through changes in the price of lumber. Secondly, in order to make the analytical discussion tractable, it is assumed that the supply curve for lumber remains at $S_{lum}^*(P^0_{lum}; P^0_i, P^0_j)$. This may be due to, among other things, the relative magnitude of the lumber market or the offsetting effects of the price changes in markets i and j.

To evaluate the welfare impacts of such a policy, three types of economic surpluses must again be considered: (1) consumer surplus, (2) quasi-rent (producer surplus), and (3) the rent created as a result of policy induced scarcity. In fact, if logs are an essential input in the production of all downstream wood processors (lumber, panels, wood pulp, wood pellets, etc), then the sum of quasi-rents in the downstream sectors must equal the consumer surplus in the log market.

As a result of the policy intervention in the log market, it is assumed that the derived demand curve for logs falls to $D_{log}(P^2_{lum}, P^1_i, P^1_j)$, leading to a change in consumer surplus equal to area (B–A). As mentioned, this may be evaluated through the change in quasi-rents in markets using logs as an essential input in production. First, the price and quantity in the lumber market (panel c) falls to P^2_{lum} and $q^1_{lum,}$ respectively, leading to a fall in quasi-rent equal to area (c+d) accruing to producers of lumber. Next, producers in market i experience a net change in quasi-rent equal to area (y+x–t) as a result of the downward shift in the supply curve. Finally, producers in the j markets complementary to lumber experience a net change in quasi-rent equal to area ($\alpha - \gamma - \eta$) as a result of the upward shift in the supply curve. Together the sum of the changes in quasi-rents in the markets downstream of logs is equal to area ($y + x + \alpha - \gamma - \eta - t - c - d$), which is exactly equal to area ($B - A$). Thus, it is only necessary to evaluate one of these surplus measures, say the sum of quasi-rents in the downstream markets to logs, and not the consumer surplus in the log market itself.

There still remain a number of other welfare measures that must be accounted for when evaluating the effects of policy intervention in the lumber market. First, the change in consumer surplus in markets downstream from logs must be taken into account and, in the case where these markets face perfectly elastic demands for their outputs, will equal the change in quasi-rents in markets consuming such products. Next, one must measure the change in quasi-rent in the upstream log market and, when faced with perfectly elastic supply for inputs, will exactly equal the change in consumer surplus in markets for factors in the production of logs. Finally, the policy induced scarcity-rent must be evaluated in the lumber market, where it may accrue to government or producers of lumber, depending on whether the policy implemented was a tax on consumption or a quota on production, respectively.

In summary, the above analysis shows that integrating additional horizontal markets to lumber will change the welfare analytics compared to the strictly vertical case in three distinct ways. First, markets whose production is either competitive or complementary in production must be considered independent from one another when evaluating the effects of policy in vertically and horizontally connected markets. Second, the appropriate welfare measures include the sum of consumer surpluses, quasi-rents and scarcity-rents in the downstream markets that use logs as inputs, plus the quasi-rent accruing to upstream log suppliers. Finally, the change in consumer surplus in the log market may be evaluated through the sum of quasi-rents in the downstream markets using logs as inputs. Similar to the earlier discussion, the results hinge on the assumption that remaining upstream and downstream markets are characterized by perfectly elastic output demand and input supply, respectively. However, it is no longer predicated on the assumption that other wood product markets (horizontal markets to lumber) are characterized by a perfectly elastic demand function or that lumber production is the only downstream user of logs.

A.5 A Model of Global Trade in Forest Products

Despite their usefulness for evaluating policy, analytic models have deficiencies that can only be addressed with an appropriate numerical model. Because a country's domestic forest product sector is inevitably linked to international markets, economic policies related to log export policies, sales of log from public forest lands and the domestic wood-products processing sector must be viewed in the context of their impacts on foreign markets. Not only is the forest products industry connected through international trade, it is also comprised of many interconnected wood products. As wood fiber is generally sourced from the initial harvest of logs, the manufacturing of secondary wood products will not only be affected by the supply of logs, but also by competition for residual fiber. Indeed, the initial demand for logs is derived from the demand functions for various manufactured wood products, including lumber. Any structural shifts in the market for one of these products will inevitably impact the others.

As noted earlier, the Global Forest Products Model (GFPM) includes forest products but relies on more general trade relations – each country trades with the rest of the world, but not with other countries (Buongiorno et al. 2003; Sun et al. 2010). That is, GFPM sacrifices information on bi-lateral flows for greater product detail. In this section, we describe a trade model in which harvests of timber leads to a supply of industrial roundwood that provides the fiber for a number of downstream products: sawnwood (lumber), plywood, particleboard (OSB, waferboard and strandboard), fiberboard (MDF and hardboard), wood pulp and, wood pellets. Although lumber and plywood are the most lucrative uses of roundwood, their production also provides residuals in the form of chips and sawdust that can be used to produce fiberboard, pulp and wood pellets as indicated in Figure A.6. Finally, the harvest and process of industrial roundwood from the initial harvest produces residuals (roadside debris; tree tops, branches, other debris), which may also be used in the production of wood pellets (although this is not done here because transportation costs are often too great).

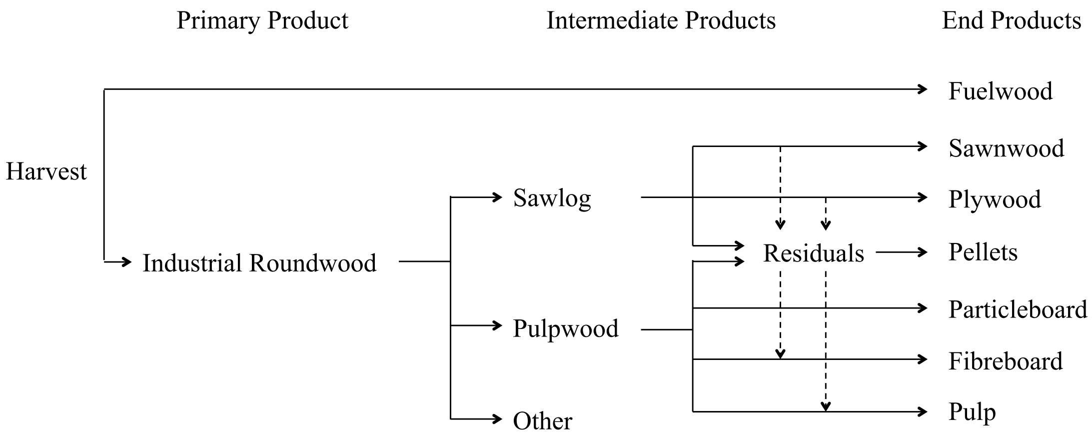

Figure A.6: Forest Product Flow Chart

The model assumes that, while changes in countries' forest policies will affect prices of forest products, they have no discernible impact on the relative prices of goods and services elsewhere in the economy. Since it is a spatial price equilibrium (SPE) trade model, it is assumed that, in the absence of trade barriers and transaction costs, prices would be the same in every region as a result of spatial arbitrage – the law of one price (LOP) holds. Differences in prices between regions are thus assumed to be the result of transaction costs, and include costs associated with shipping and handling goods (e.g., freight, insurance, exchange rate conversion fees), plus tariffs and other non-tariff barriers.

In the model, Canada is divided into five regions – Atlantic Canada, Central Canada, Alberta, BC Interior and BC Coast. The United States is divided into three regions (South, North, West), and Asia is separated into China, Japan and Rest of Asia. Chile, Australia, New Zealand, Finland, Sweden and Russia are also separate regions, while the remaining regions comprise Rest of Europe, Rest of Latin America, and the Rest of the World (ROW).

The model calculates production of logs and various wood products and their consumption in each region, and associated bilateral regional trade flows. It is solved numerically in an integrated Excel-R-GAMS environment.

Model Specification

Objective function

Consider first the wood processing sector. Each region is assumed to have a set of linear (inverse) demand and supply curves for each downstream product *k*:

$$P_d^k = \alpha_d^k - \beta_d^k q_d^k,\ \alpha_d^k, \beta_d^k \geq 0,\ \forall d = 1, \ldots, M,\ \forall k, \text{ and} \tag{A.10}$$

$$P_s^k = a_s^k + b_s^k q_s^k,\ a_s^k, b_s^k \geq 0,\ \forall s = 1, \ldots, N,\ \forall k, \tag{A.11}$$

where $k \in$ {lumber, plywood, particleboard, fiberboard, pulp, wood pellets}, q_d^k refers to the quantity of commodity *k* consumed in demand region *d*, and q_s^k refers to the quantity of wood product *k* produced by supply region *s*.[28] There are *M* demand (import) regions and *N* supply (export) regions and, for convenience of notation, these are assumed to be the same for each product *k*. One objective of the forest trade model is to maximize the sum of the consumer and producer surpluses across all relevant wood-processing sectors. The consumer and producer surpluses are found by maximizing the sum of the areas under the *M* demand schedules (A.10) and subtracting the sum of the areas under the *N* supply schedules (A.11). These respective areas are given by:

$$B_d^k = \int_0^{q_d^k} (\alpha_d^k - \beta_d^k x)\,dx = \alpha_d^k q_d^k - \frac{1}{2}\beta_d^k q_d^{k^2}, \text{ and,} \tag{A.12}$$

$$C_s^k = \int_0^{q_s^k} (a_s^k + b_x^k x)\,dx = a_s^k q_s^k + \frac{1}{2} b_s^k q_s^{k^2}, \tag{A.13}$$

where *x* is an integration variable, B_d^k is the total benefit (area under demand) in demand region

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[28] For convenience, we use *d* to denote a net demand region and *s* a net supply region, although a region is simultaneously a supplier and demander of the commodity in question.

d for product *k*, and C_s^k is the total cost (area under supply) in supply region *s* for product *k*.[29]

Now consider the markets for industrial roundwood (pulp logs and coniferous logs). As noted earlier, the demand for logs is a derived demand that depends on the production of downstream lumber, plywood, pellets, pulp, et cetera. For each wood product *k*, its derived demand is given by its output price multiplied by the marginal physical product of the input (logs) in the production of the k^{th} commodity: $P^k \times \text{MP}_{logs \rightarrow \text{k}}$. The total derived demand for logs is given by the horizontal sum of the individual *k* derived demands for logs. However, the change in consumer surplus in the log market caused by a policy shock can be evaluated in the downstream markets, namely, as the sum of the changes in the producer surpluses in the downstream wood processing markets – changes in the consumer surplus in the log market are measured by the changes in producer surpluses in the downstream markets. Thus, it is necessary to include in the objective function only the producer surplus in the log market. Assume that the supply (marginal cost) of logs in region *u* is linear: $r_u = m_u + n_u Q_u$, m_u, $n_u \geq 0$, where Q_u is the quantity of logs in country *u*. The producer surplus from supplying logs from any region *u* is:

$$QR_u = r_u Q_u - \int_0^{Q_u} (m_u + n_u x) dx = \frac{1}{2} n_u Q_u^2, \forall u = 1, \ldots, U, \tag{A.14}$$

where *U* regions supply logs.[30]

The overall objective in the forest trade model is to maximize the sum of the necessary producer and consumer surpluses provided above, while subtracting the shipping and handling costs and associated taxes. The objective function to be maximized can be written as:

$$W = \sum_{k=1}^{K} \left[\sum_{d=1}^{M} B_d^k - \sum_{s=1}^{N} C_s^k - \sum_{d=1}^{M} \sum_{s=1}^{N} \left(t_{s,d}^k + \tau_{s,d}^k \right) q_{s,d}^k \right] + \sum_{u=1}^{U} \left[QR_u - \sum_{s=1}^{N} \left(\delta t_{u,s} + \tau_{u,s} \right) Q_{u,s} \right], \tag{A.15}$$

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[29] See Vercammen (2011, p.22). Given lack of good data, in the numerical analysis a supply elasticity of one is assumed, which implies that the supply schedules pass through the origin. Vercammen also provides the welfare equation if supply schedules intersect the horizontal axis (have negative intercepts).

[30] In the current specification, we do not distinguish among different log types; this is done below, in which case the objective function (equation 29 below) will change slightly to include this distinction.

where W refers to the overall global wellbeing from trade in forest products, $t_{s,d}^{k}$ is the cost ($\$/m^3$) of transporting processed forest product k from supply region s to demand region d, and $\delta t_{u,s}$ is the cost of transporting industrial roundwood (logs) from region u to region s, where δ is a parameter that takes into account the extra cost of transporting logs because they occupy more space per cubic meter than lumber (whose cost of transport from region u to s is given by $t_{u,s}$).[31] Finally, $\tau_{u,s}$ is the tax on logs ($\$/m^3$) originating in log supply region u and sold to wood product producing region s, while $\tau_{s,d}^{k}$ is the tax on wood product k originating in supply region s and exported to region d.

Objective (A.15) is maximized subject to a series of biophysical and economic constraints relating to the availability of timber harvests, log supply and wood product manufacturing limits.

Constraints

The essential constraints are material flows and productivity constraints that ensure that total supply equals total demand for each region/country and each product. The model constraints are summarized as follows. First, the quantity of industrial roundwood of each type $L \in$ {saw logs, veneer logs, pulpwood logs} = {SL, VL, PL} produced by any log producing region u must be no greater than its harvest of logs (h_u), and the region's ability to convert harvested timber into various industrial roundwood components:

$$Q_u = \sum_{L \in \{SL, VL, PL\}} Q_u^L \leq \phi_u^L \times h_u, \forall u. \tag{A.16}$$

The parameter ϕ_u^L indicates how much coniferous industrial roundwood of each type is recovered from the timber harvest in region u, which depends on size and species of trees, as well as the region's technical skills, capital and other factors. The aggregate of the various log types in region u is denoted Q_u. The sale of logs by region u to log consuming regions s, including domestic sales, must not exceed the total supply of logs in region u:

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[31] In the current application, $t_{s,d}^{k} = t_{s,d}^{lum}$ for all k.

$$\sum_{s=1}^{N} Q_{u,s}^{L} \leq Q_{u}^{L}, \forall u, L. \tag{A.17}$$

The quantity of logs supplied to region *s* must be greater than or equal to the amount required for the production of downstream wood products:

$$\sum_{u=1}^{U} Q_{u,s}^{L} \geq Q_{s}^{L}, \forall\ s, L. \tag{A.18}$$

Logs are used as inputs into the production of the *K* downstream wood products. It follows that the sale of downstream wood products from supplying region *s* to all consuming regions must be no larger than what is produced in region *s*:

$$\sum_{d=1}^{M} q_{s,d}^{k} \leq q_{s}^{k}, \forall\ s, k. \tag{A.19}$$

Similarly, the supply of downstream products from all supply regions to region *d*, and including domestic supply, must be greater than or equal to the demand of region *d*:

$$\sum_{s=1}^{N} q_{s,d}^{k} \geq q_{d}^{k}, \forall\ d, k. \tag{A.20}$$

We distinguish between primary and secondary wood products processed from logs on the basis of value – primary products generally tend to be quite a bit more valuable than secondary products (but not always).[32] Lumber and plywood must necessarily be considered primary products for sawlogs (*SL*) and veneer logs (*VL*), while wood pulp is the primary product from pulp logs (*PL*). In addition, secondary products (particleboard, fiberboard and wood pellets) can employ wood fiber from logs in direct competition with the primary products, with wood pulp also considered a secondary product when it comes to non-pulp logs. Therefore, in what

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[32] A secondary product may be more valuable depending on the quality of logs and the location of processing facilities. Consider as an example fast-growing pine plantations located next to a power plant; the pine is grown primarily to be used as a biomass fuel. Alternatively, such trees might be best used to produce pulp if no sawmills are in the vicinity.

follows, we denote $f \in \{\text{particleboard, fiberboard, pulp, pellets}\} \subset K$ and $nf \in \{\text{lumber, plywood}\} \subset K \ni f \cup nf = K$.

Secondary products will rely on chips and residuals from sawmilling and plywood manufacture for the most part. For simplicity, however, we assume that industrial roundwood gets allocated to each of our six (primary plus secondary) products so that all of the roundwood is utilized. This can be described using the following relation:

$$q_s^{k,L} \leq \rho_s^{k,L} \times \eta_s^{k,L} \times Q_s^L, \forall\, k, s, L. \tag{A.21}$$

In equation (A.21), the total available output in processing region *s* of wood product *k* from logs of type *L*, $q_s^{k,L}$, is determined by the proportion of the logs of type *L* used to produce *k*, denoted $\rho_s^{k,L}$, multiplied by the recovery factor $\eta_s^{k,L}$ that converts logs into product and the amount of logs of type *L* available in region *s*. To ensure that all of the wood fiber is fully used we require

$$\sum_{k=1}^{K} \rho_s^{k,L} = 1. \tag{A.22}$$

The manufacture of lumber and plywood results in chips and other residuals (sawdust, planer shavings, residues) that are joint products that can be used to produce particleboard, fiberboard, wood pulp and wood pellets. The total amount of wood chips and residuals produced in region *s* depends on the production of lumber and plywood, and can be determined from the following relation.

$$R_s^z = \sum_{nf} \left(q_s^{nf} \times v_s^{nf,z} \right), \forall\, s, z \in \{\text{wood chips, other residuals}\}, \tag{A.23}$$

where R_s^z is the amount of *z* (wood chips, sawdust, planer shavings or other residuals) produced in region *s* and $v_s^{nf,z}$ is the region's ability to recover residual *z* from each of the sawmilling and plywood manufacturing sectors.

The production of products *f* directly from logs in region *s* is denoted $q_s^{f,L}$ and is determined from equation (A.21). In addition, we find the amount of product *f* produced from chips and residual fiber using the following relationship:

$$q_s^{f_R} = \sum_z \left(w_{s,f}^z \times \theta_f^z \times R_s^z \right), \forall s, \tag{A.24}$$

where $q_s^{f_R}$ denotes the quantity of wood product *f* produced from residual fiber (and not directly from logs). In addition, $w_{s,f}^z$ refers to the proportion of residual fiber of type *z* in region *s* that is used to produce product *f*, while θ_f^z is a parameter that converts residual fiber of type *z* into product *f*. The condition requiring that all residual fiber is exhausted is given by:

$$\sum_f w_{s,f}^z, \forall s, z. \tag{A.25}$$

Pulp mills use chips from sawmilling and manufacture of plywood to the extent that such chips are not used for OSB or other products. Particleboard, fiberboard and pellets can employ wood chips and other residuals from sawmilling and plywood production.

Finally, the total amount of product *k* produced by region *s* can now be determined as follows:

$$q_s^k = q_s^{f_R} + \sum_{L \in \{\text{SL,VL,PL}\}} q_s^{k,L}, \forall s, k, f \in k. \tag{A.26}$$

The constrained optimization program maximizes objective (A.15) subject to constraints (A.16) through (A.26) plus non-negativity conditions on the decision variables. For each of the relevant regions, the decision variables are the supply of industrial roundwood (sawlogs and veneer logs) and pulpwood (Q_u^L); bilateral flows of logs from supplying to wood processing regions ($Q_{u,s}^L$); production and consumption of product *k* in each region (q_s^k and q_d^k, respectively); and the bilateral trade flows of product *k* ($q_{s,d}^k$). The proportions of the logs of type *L* used to produce *k* ($\rho_s^{k,L}$), and the proportions of residual fiber of type *z* used in *f* ($w_{s,f}^z$) can also be determined endogenously in the model, although, in the current application, these are exogenously provided.

Model Calibration: Positive Mathematical Programming

It is important that the forest trade model is calibrated so that the user can be confident that model projections are realistic. The calibration must be based on observed values and must be rooted in economic theory. Although trade models rely on observed data, it is often the case that computational deficiencies require an aggregation of firm and market characteristics. As a result, mathematical programming models of trade often experience extreme specialization in supply responses. As well, discrepancies between modelled and observed optimal values may arise due to mis-specified parameters, often originating from transaction costs per unit of product traded between two countries (e.g., non-tariff trade barriers). To deal with such problems, several calibration techniques have evolved.

One method is referred to as the historical mixes approach, which attempts to address the problem of extreme solutions (McCarl 1982; Önal and McCarl 1991). This approach is based on the fact that optimal solutions are often found at corners (extreme points), particularly when working with aggregate representative producers.[33] Since aggregation may bias the data, and hence the original problem, a region may be assigned a subset of possible production 'mixes' based on observed levels. This last point is justified as observed mixes must be optimal, or why would they have occurred in the first place? This calibration method takes historical choices (mixes) into account by constraining the current optimal values to be a weighted average of those observed choices. The weights may be determined endogenously within the mathematical programming framework, with the sum of the weights equaling 1. Chen and Önal (2012) extend this method by including decisions that are not historically observable. Simulated mixes of the 'new' decision variables are added to the historical mixes, allowing the optimization procedure to choose the weights, and again constraining the sum of the historical and synthetic weights to equal 1.

A second calibration method based on an approach originally proposed by Howitt (1995), referred to as positive mathematical programming (PMP), is increasingly applied to problems in agriculture and forestry (see de Frahan et al. 2007; Paris 2011, pp.340-411; Heckelei et al. 2012). Positive mathematical programming uses the notion that any calibration constraint can be represented in the objective function (e.g., a linear calibration constraint might be represented as

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[33] The simplex method that is used in solving linear and quadratic programming problems finds only corner solutions.

a nonlinear cost function in the objective). Rather than adding arbitrary calibration constraints to ensure that the optimal solution to a mathematical program replicates what is observed (as in the historical mixes approach), the PMP method uses the shadow prices associated with such constraints to re-specify the objective function. The calibrated model is then solved to replicate the observed values exactly.

In trade models, the PMP-calibrated ‘transportation’ costs represent the ‘effective’ transaction costs between export and import regions. They are derived from the shadow prices on the calibration constraints relating to the observed flows of logs and lumber. Again the calibration is motivated by the fact that there is a discrepancy between the true transaction costs and the observed transaction costs, as determined by shipping, loading/unloading, insurance and administrative costs, plus tariffs and non-tariff barriers. The main reason for this discrepancy occurs because (observed) transaction costs are measured with a significant degree of uncertainty (Paris et al. 2011). To deal with and measure the hidden or unknown transaction costs (bribes, non-tariff barriers, etc.), one can utilize a two-phase positive mathematical programming model (Paris et al. 2011).

The phase I PMP specification maximizes objective (A.15) subject to constraints (A.16)-(A.26), with the addition of the following constraints:

Dual Variable

$$Q^{L}_{u,s} = \overline{Q}^{L}_{u,s} \qquad\qquad \lambda^{L}_{u,s} \qquad\qquad \text{(A.27)}$$

$$q^{k}_{s,d} = \overline{q}^{k}_{s,d} \qquad\qquad \lambda^{k}_{s,d} \qquad\qquad \text{(A.28)}$$

In this specification, it is assumed we observe trade flows for industrial roundwood and *k* downstream wood products, $\overline{Q}^{L}_{u,s}$ and $\overline{q}^{k}_{s,d}$, as well as their respective transaction costs $\delta t_{u,\mathrm{s}}$ and $t^{k}_{s,d}$.

Upon obtaining the shadow prices $\lambda^{L}_{u,s}$ and $\lambda^{k}_{s,d}$ associated with the primal model, the objective function for the phase II problem can be specified as follows:

$$\text{Maximize } W = \sum_{k=1}^{K}\left[\sum_{d=1}^{D} B^{k}_{d} - \sum_{s=1}^{S} C^{k}_{s} - \sum_{d=1}^{D}\sum_{s=1}^{S} T^{k}_{s,d} q^{k}_{s,d}\right] + \sum_{L\in\{SL,VL,PL\}}\sum_{u=1}^{U}\left[QR_{u} - \sum_{s=1}^{S}\delta T^{L}_{u,s} Q^{L}_{u,s}\right], \qquad \text{(A.29)}$$

where $T^k_{s,d}$ now equals $t^k_{s,d} + \tau^k_{s,d} + \lambda^k_{s,d}$, and $T_{u,s}$ equals $t_{u,s} + \tau_{u,s} + \lambda^L_{u,s}$. In the second stage, the modified objective function (A.29) is maximized subject to the original constraints (A.16)-(A.26). With this modification, the model precisely duplicates the inter-regional fiber trade flows.

The fact that the shadow prices $\lambda^L_{u,s}$ and $\lambda^k_{s,d}$ can be negative indicates that the original transaction cost data fail to include missing policy instruments, such as export subsidies. Indeed, Paris et al. (2011) indicate that, in some instances, the overall effective transaction costs between two countries might even be negative, as when export subsidies are larger than the sum of other transaction costs. In some circumstances, this may provide additional insight into the potential restrictiveness of trade measures that are otherwise difficult to quantify, such as non-tariff trade barriers (e.g., phytosanitary standards).

Economic Surplus and Income Redistribution

As discussed in Section A.4, the appropriate welfare areas are the consumer surplus and quasi-rent (producer surplus) in the downstream markets, plus the quasi-rent and resource rent accruing in the log markets. In addition, there may be policy-induced scarcity rents that accrue to governments in the form of tariffs or taxes and to other economic agents as quota rents; some of this rent is simply wasted in rent-seeking activities or lost due to other inefficiencies. In the model these welfare measures and income transfers are calculated ex post – after the model has solved the optimal bilateral trade flows. The following equations provide the mathematical derivation of these welfare measures.

Wood Processing Sector

Consider first the k downstream wood processing markets in the vertical supply chain. The consumer surpluses in each of these markets and each commodity are given by:

$$CS^k_d = \int_0^{q^k_d} \left(\alpha^k_d - \beta^k_d x\right) dx - P^k_d q^k_d = \left(\alpha^k_d q^k_d - \frac{1}{2}\beta^k_d (q^k_d)^2\right) - \left(\alpha^k_d - \beta^k_d q^k_d\right) q^k_d = \frac{1}{2}\beta^k_d (q^k_d)^2, \forall s,k, \quad \text{(A.30)}$$

where P^k_d is the demand price for product k in the domestic market, and q^k_d is the quantity of product k consumed. Likewise, the producer surpluses or quasi-rents in these k downstream markets are given by:

$$QR_s^k = P_s^k q_s^k - \int_0^{q_s^k} \left(a_s^k + b_s^k x\right) dx = \left(a_s^k + b_s^k q_s^k\right) q_s^k - \left(a_s^k q_s^k + \frac{1}{2} b_s^k (q_s^k)^2 \right) = \frac{1}{2} b_s^k (q_s^k)^2, \ \forall s,k, \qquad \text{(A.31)}$$

where P_s^k is the supply price for product k in the domestic market, and q_s^k is the quantity of product k produced.[34]

In each of the downstream markets, a variety of distortions might exist. These consist of tariff and non-tariff trade barriers, export taxes, illegal fees, quotas and so on. These distortions to trade are captured in the PMP calibration process so that they are included in the revised shipping, handling and other transaction costs (see below). However, when we examine the impact of various policies (e.g., tariff or export tax, quota), income transfers will occur and these can be measured in two ways. First, with tariffs or taxes, the income accrues to government and is calculated simply as the quantity affected (traded or sold) multiplied by the tariff/tax rate. Second, some policies create distortions that result in a wedge between the demand price and the supply price (or marginal cost). This leads to a policy-induced scarcity rent that is calculated as follows:

$$SR_y^k = (P_y^{k,Demand} - P_y^{k,Supply})\bar{q}_y^k = \left\{\left(\alpha_y^k - \beta_y^k \bar{q}_y^k\right) - \left(a_y^k + b_y^k \bar{q}_y^k\right)\right\}\bar{q}_y^k, \ \forall k, y \in \{s,d\}, s \neq d, \qquad \text{(A.32)}$$

where $\bar{q}_y^k$ refers to the quantity of k consumed in market y. In essence, since the producer surplus calculated in equation (A.33) does not include the policy-induced scarcity rent, it is necessary to include this rent as a transfer, although it is not clear who captures this rent; it is simply determined by the size of the wedge between the demand and supply prices multiplied by the quantity sold in market y ($\bar{q}_y^k$).

Upstream Log Markets

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[34] It might be worth recalling that, in principle, a region might only be a supply or demand region, but in practice regions both supply and demand each of the k products. Further, given the regions in the model are quite large, each supplies some amount of harvested timber to its domestic market for processing.

Now turn to the market for logs. As noted earlier, because the demand for logs is a derived demand, the consumer surpluses in the log markets are measured as quasi-rents in the *K* downstream markets. It is necessary, therefore, only to measure the producer surplus or quasi-rent in the log markets. The best measure of the quasi rent in any log market is given by equation (A.14) and is similar to equation (A.33); it is given by:

$$QR_u^L = \frac{1}{2} n_u^L (Q_u^L)^2, \forall u, L, \tag{A.33}$$

where n_u^L is the slope of the type-*L* log supply curve in region *u*.

To this, must be added any scarcity rent associated with resource scarcity or the result of the introduction of policy that creates a wedge between the demand and supply price of logs. Because we do not explicitly include demand functions for logs in the trade model, we rely on the shadow prices of logs. The shadow price of logs gives the addition to global wellbeing, as defined in the objective function (A.15), if an additional log were available. Therefore, policy-induced rent plus the rent from resource scarcity in the log market can be calculated by the shadow price of logs times the volume produced:

$$SR_u^L = \lambda_u^L \overline{Q}_u^L, \forall u, L, \tag{A.34}$$

where λ_u^L is the shadow price and $\overline{Q}_u^L$ is the equilibrium production of logs of type *L* in region *u*.

The surpluses in equations (A.30)-(A.34) are summed to obtain the total surplus from trade.

Model Data

The underlying data come from a variety of sources and are provided in Appendix A. The Food and Agriculture Organization of the United Nations (FAO 2014) constitute the primary source of forestry statistics, while supplementary data are available from the Government of Canada (2012), BC Statistics (2013), Random Lengths (various years), the University of Washington's

Center for International Trade in Forest Products (CINTRAFOR),[35] the Global Forest Products Model at the University of Wisconsin (GFPM),[36] the U.S. Forest Service (e.g., Howard 2001; Oswalt et al. 2009; Warren 2011), the United Nations Economic Commission for Europe (UNECE),[37] and van Kooten and Johnston (2014). Where FAO data were either unavailable, or observations were missing, supplementary data were used.

The FAO provides annual production and trade data for a number of forest products dating back to 1961. The data are collected through annual questionnaires conducted by the FAO Forestry Department in partnership with the International Tropical Timber Organization, the Statistical Office of the European Communities (Eurostat), and the UNECE. In cases where countries fail to provide information through the questionnaire, the FAO estimates production and trade of wood products through trade journals, statistical yearbooks and other sources. Where data are unavailable, the FAO repeats historical information from the previous years. Although, in some instances the quality of the FAO data may be less than desired (Buongiorno et al. 2001), they are nonetheless consistently available at a country level, and provide information on the destinations of various forest product exports and the origins of imports. Having this information is critical for implementing the positive mathematical programming calibration method on country-to-country trade flows. Since Canada and the U.S. are broken down into five and three sub-regions, respectively, the FAO data had to be adjusted using local information. Further, information from Canada and the U.S. was used to reconcile missing observations from the FAO dataset.

The data analysis began with the collection and calculation of each region's technical

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[35] Center for International Trade in Forest Products. University of Washington School of Environmental Forest Services. http://www.cintrafor.org/research/tradedata.shtml (Accessed January 10, 2014). See also Perez-Garcia (1993).

[36] Data are available from Buongiorno at http://labs.russell.wisc.edu/buongiorno/ (viewed 22 January 2013). Although it includes a plethora of forest products, the University of Wisconsin's forest trade model was not used because of its drawbacks. For the current purposes, these include its lack of small, sub-country regions. Further, each country trades with a central auctioneer rather than amongst each other, so there is no bilateral trade information (e.g., see Sun et al. 2010).

[37] United Nations Economic Commission for Europe. http://www.unece.org/fileadmin/DAM/timber/docs/dp/dp-30.pdf (Accessed December 12, 2013).

ability to produce logs and wood products. First, a region's ability to produce logs is a function of the annual allowable cut (AAC), which is the amount of wood permitted to be sustainably harvested, and a region's ability to convert coniferous logs into industrial roundwood. Data on AAC are available from FAO, the U.S. Forest Service (Howard 2001; Oswalt et al. 2009), and the Canadian Forest Service's National Forestry Database (Government of Canada 2012). Factors converting harvested coniferous timber into industrial roundwood were determined by taking ratios of each region's production of roundwood to harvests. Industrial roundwood is assumed to be broken down into two sub-categories: (1) sawlogs and veneer logs, and (2) round and split pulpwood. For both categories, the FAO provides regional production and trade flows. However, in the current model we are not concerned to replicate pulpwood trade as there is simply too little trade of pulpwood.

Next, the ability to recover coniferous wood products (lumber, plywood, particleboard, fiberboard, pulp and wood pellets) from their respective log inputs is calculated as the ratio of production to inputs. The FAO differentiates coniferous from non-coniferous lumber allowing for a simple calculation of regional coniferous lumber recovery factors. This is not the case for other wood products, however. First, plywood and veneer sheets are reported as an aggregate of coniferous and non-coniferous fiber by the FAO. Thus, to estimate regional coniferous plywood and veneer sheet production, the reported aggregate data were adjusted by taking the proportion of coniferous sawlogs and veneer logs consumed in a region multiplied by total regional production of plywood and veneer sheet. A similar adjustment was applied to particleboard. Fiberboard and pulp were also reported as an aggregate of softwood and hardwood by the FAO. As these products primarily use fiber from pulpwood, they were adjusted using the reported proportion of regional coniferous pulpwood consumption multiplied by the total aggregated production of the respective product. Wood pellet data were collected irrespective of whether pellets were produced using coniferous or non-coniferous fiber. The FAO does not currently report on wood pellet statistics directly; thus, we rely on other sources (e.g., Lamers et al. 2012; Government of Canada 2012; EuroStat 2013) and adjust regional production based on the proportion of coniferous industrial roundwood consumption by each region. Finally, a region's ability to recover chips and residuals from sawmilling is determined from a variety of sources (BC Government 2009; UNECE 2010; Government of Canada 2010).

Regional consumption of logs and wood products is based on apparent consumption (production + imports – exports) since the FAO only reports production and trade. For Canada and the United States, regional consumption of logs is determined by production, while regional exports of logs are allocated on the basis of various statistical sources (e.g., BC Statistics 2013) and trade publications (*Random Lengths*).[38] Regional wood product consumption in Canada and the U.S., on the other hand, was determined by allocating total consumption across regions by their proportion of population. The same was done with respect to regional imports – national imports were allocated across regions according to population. Exports from any Canadian or U.S. region to any other country/region in the model were derived by allocating national exports to those countries/regions by regional production, but then making adjustments based on other sources of information.

It is important to note that, in many circumstances, bi-lateral trade flows of wood products are reported by the FAO as an aggregate of coniferous and non-coniferous products. Thus, the trade matrices for aggregated products were adjusted in a similar fashion to production. Specifically, exports from a given country were adjusted based on the proportion of coniferous inputs used in the respective region. The trade matrices are provided in Appendix Tables A-7 to A-13. At this time, there is too little information on the country-to-country trade flows of wood pellets to be included in the calibration component of the model.

Data on prices come primarily from *Random Lengths* and the timber database of the UNECE (2014), reported in Table A-3. The base-year AAC and production of logs and wood products are provided in Table A-1, while consumption is provide in Table A-2. The price elasticities of demand for wood products are derived from a variety of sources (FAO 2014; BC Stats 2013; Oswalt et al. 2009; van Kooten and Johnston 2014) and are reported in Table A-5. As noted earlier, for simplicity and because data are not available for most regions, log and lumber supply elasticities are assumed to equal 1.0; then the slopes of these schedules are simply given by the ratios of the base production (manufacturing) costs provided in Table A-4 and outputs.

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[38] Various issues of *Random Lengths* are employed. Regional production of lumber was first based on regional production of coniferous roundwood using forestry statistics from the Government of Canada (2012) and BC Statistics (2013) for Canada, and Howard (2001), Oswalt et al. (2009) and Warren (2011) for the U.S. Population data are from Statistics Canada and the U.S. Census Bureau, while world population data are from the FAO (2014). The authors can provide data and calculations upon request.

The manufacturing costs come primarily from UNECE (2012) or van Kooten and Johnston (2014).

The shadow prices associated with the calibration constraints in the first phase of the PMP procedure are provided in Tables B-1 to B-6. The shadow prices are then used to adjust the observed transportation and other transaction costs (Table A-6) to calculate the effective transportation costs, which are provided in Tables C-1 to C-6. For log shipments, the transportation costs are identical to those for lumber, but are multiplied by δ (=1.27) to account for the extra volume required to transport logs compared to lumber. Because constraints (A.29) and (A.30) are equality constraints, the associated shadow prices may be either positive or negative. As noted earlier, a positive shadow price indicates that the effective transportation and other transaction costs are higher than observed, perhaps because transportation costs have been underestimated or there exist unobserved non-tariff costs (as noted earlier). Likewise, there may be subsidies or other policies that not taken into account, in which case the shadow prices are negative.

A.6 Conclusions

In this Appendix, we provide the theoretical foundation for a spatial, price-equilibrium forest trade model that included upstream log harvesting and downstream wood processing – a vertical chain with horizontal layers. We then developed a mathematical representation of the trade model; this took the form of a constrained optimization model or, more specifically, a quadratic programming model. The model tracks ten different forest products and their associated country-to-country trade flows. The products consisted of three different log types, six final products and an intermediate product (residuals) derived during the processing stage. Residuals took various forms but could be inputs into four final products, although these products could also be produced directly from logs. In addition, the model has 20 regions, of which five are in Canada and three in the United States. Since data are generally provided at a country-level, a method was developed to allocate supply and demand to regions within a country.

The model differs from previously models in several important ways. Although the majority of the forest product trade models have employed the same spatial price equilibrium framework employed here, the documentation included with most models has lacked a clear explanation of the underlying economic theory upon which the model is built, or the documentation is unavailable. In the development of a model with vertical and horizontal chains, it is important to determine how markets relate and how welfare changes are measured. In the current application, policies that affect one market might result in large changes in wellbeing of economic agents in various markets, but these are often income transfers and not true measures of the global change in welfare (see van Kooten 2014). That is, many trade policies that countries or regions pursue are best considered to be of the 'beggar-thy-neighbor' type.

Further, positive mathematical programming is used to calibrate country-to-country trade flows to observed bilateral trade in some base period. This contrast with previous models of forest trade that generally calibrate trade flows by minimizing the difference between observed and estimated values. Ad hoc constraints are then employed to achieve a 'best' calibration. The PMP method is rooted in economic theory and reduces the remaining error to zero without the need for ad hoc constraints: that is, the PMP-calibrated model can reproduce observed trade flows exactly. Further, PMP is useful where there are no observable data, particularly where transaction costs and/or policies are not properly taken into account. It should be noted, however, that if the underlying model data are sparse, or incorrectly taken into account, the PMP method may still prove to lead to errors. Indeed, one line of future research would be to use the PMP approach not only to calibrate bilateral trade flows to those observed in a given period, but also use it to calibrate the model to replicate the output of forest products to the base period.

The quality of the data underlying the model is open to criticism. Although much effort has been expended to ensure that the data are the best available, the data provided by the primary source (FAO 2014) are based on the completion of surveys by various country forest ministries. Depending on the quality of data available in any given country, whether the survey has been sent to the appropriate ministry or office that has access to the data, and the effort of the person responsible for responding will determine the quality of data. The result is uneven quality of data. Yet, the FAO database is the only readily available comprehensive forest data that provides distinct country-to-country trade flows, which is critical in implementing the PMP calibration.

Finally, the current model employs fixed country-specific recovery factors. Making the factors endogenous would alleviate some of the rigidity in the model, facilitating greater flexibility. The model would also greatly benefit from the inclusion of dynamic considerations, although making the model truly a dynamic optimization (requiring equations that tie one year to another, say through investment) is likely beyond the current state of the art in forest trade modelling. Rather, a dynamic model is more likely to rely on exogenous variables to relate periods over time. Clearly, future research is required and it could start with the current model.

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Addendum A – Input Data

Table A-1: Global Coniferous AAC and Forest Product Production in 2011

Country/Region	AAC ('000 m^3)	Industrial Roundwood ('000 m^3)	Sawlogs + Veneer Logs ('000 m^3)	Pulpwood ('000 m^3)	Sawnwood ('000 m^3)	Plywood + Veneer[1] ('000 m^3)	Particleboard[1] ('000 m^3)	Fibreboard[1] ('000 m^3)	Pulp[2] ('000 Mt)	Wood Pellets ('000 Mt)
Australia	29,788	14,912	8,988	5,632	3,826	213	773	474	491	204
BC Coast	45,802	13,729	12,316	1,144	4,451	371	607	111	1,915	0
BC Interior	62,246	53,225	48,074	4,107	15,984	1,331	2,181	399	6,877	1,196
Alberta	15,780	14,839	13,403	1,145	4,457	58	883	162	1,917	76
Atlantic Canada	13,052	10,393	9,388	802	3,121	88	5	1	474	237
Rest of Canada	33,268	31,285	28,257	2,414	9,395	287	2,621	480	1,427	355
Chile	47,215	26,454	15,523	10,412	6,631	1,281	521	958	2,125	38
China	291,251	42,587	37,613	4,139	17,918	30,539	8,180	31,575	6,340	384
Finland	50,952	39,122	18,763	19,592	9,700	1,013	163	96	7,812	275
Japan	17,281	16,306	13,877	2,109	9,294	2,518	949	825	4,059	30
New Zealand	21,956	11,788	8,245	3,312	3,934	1,053	145	674	1,432	59
Russia	173,000	94,013	65,700	26,470	29,055	2,799	5,204	1,491	5,267	1,265
Sweden	70,200	62,960	33,600	28,125	16,400	112	507	96	10,342	1,332
US North	23,505	13,901	8,645	4,983	3,138	535	806	416	1,893	894
US South	218,289	129,093	80,282	46,281	29,144	4,970	7,482	3,860	17,577	1,076
US West	98,861	58,465	36,359	20,960	13,199	2,251	3,388	1,748	7,960	246
Rest of Latin America	443,222	5,472	5,009	356	2,621	713	410	120	0	3
Rest of Europe	347,306	181,725	122,032	56,130	73,755	3,941	31,570	12,935	10,399	6,089
Rest of Asia	697,010	6,008	3,871	2,019	6,148	951	243	435	439	1
Rest of World	734,894	113,090	82,552	28,321	37,628	35,254	14,298	38,087	6,295	9
TOTAL	**3,434,878**	**939,368**	**652,495**	**268,454**	**299,799**	**90,278**	**80,936**	**94,943**	**95,042**	**13,769**

Source: FAO (2012), BC Statistics (2013), Government of Canada (2012), Oswalt et al. (2009), van Kooten and Johnston (2013), UNECE (2012)

[1] Calculated by the author based on proportion of coniferous sawlogs + veneer logs out of total sawlogs + veneer logs multiplied by total plywood + veneer production from FAOSTAT - Forestry database

[2] Calculated by the author based on proportion of coniferous pulpwood out of total pulpwood multipled by total pulp production within a given country from FAOSTAT - Forestry database.

[3] Calculated by the author based on the proportion of coniferous industrial roundwood out of total industrial roundwood production within the given country from FAOSTAT - Forestry database.

Table A-2: Global Coniferous Forest Product Consumption in 2011

Country/Region	Industrial Roundwood ('000 m^3)	Sawlogs + Veneer Logs ('000 m^3)	Pulpwood ('000 m^3)	Sawnwood ('000 m^3)	Plywood + Veneer[1] ('000 m^3)	Particleboard[1] ('000 m^3)	Fibreboard[1] ('000 m^3)	Pulp[2] ('000 Mt)	Wood Pellets ('000 Mt)
Australia	14,912	8,196	5,632	4,394	489	811	205	654	0
BC Coast	13,729	9,554	1,144	1,686	316	630	166	1,335	0
BC Interior	53,225	47,789	4,107	1,943	866	2,169	410	4,742	49
Alberta	14,839	13,667	1,145	1,771	120	904	216	1,119	4
Atlantic Canada	10,393	9,460	802	1,492	105	23	36	54	11
Rest of Canada	31,285	29,561	2,414	9,367	701	2,778	798	273	17
Chile	26,454	15,472	10,412	4,546	166	539	824	434	38
China	42,587	49,533	4,139	28,179	25,523	8,169	29,957	13,624	384
Finland	39,122	20,336	19,592	5,037	261	224	207	6,022	182
Japan	16,306	16,241	2,109	15,549	3,449	384	562	5,010	158
New Zealand	11,788	5,901	3,312	1,708	554	103	291	660	10
Russia	94,013	47,855	26,470	16,898	1,485	5,282	1,749	4,075	392
Sweden	62,960	35,070	28,125	5,861	231	791	259	8,935	1,869
US North	13,901	8,958	4,983	30,254	1,649	1,599	1,237	309	552
US South	129,093	77,615	46,281	15,831	5,001	7,914	4,025	12,737	567
US West	58,465	35,225	20,960	12,729	2,453	3,711	1,882	4,870	152
Rest of Latin America	5,472	5,148	356	3,500	1,450	417	847	979	0
Rest of Europe	181,725	119,368	56,130	88,283	4,672	27,178	7,033	5,688	9,316
Rest of Asia	6,008	12,718	2,019	7,062	1,744	898	1,254	13,052	2
Rest of World	113,090	84,829	28,321	43,711	39,044	16,413	42,987	10,470	1
TOTAL	**939,368**	**652,495**	**268,454**	**299,799**	**90,278**	**80,936**	**94,943**	**95,042**	**13,704**

Source: FAO (2012), BC Statistics (2013), Government of Canada (2012), Oswalt et al. (2009), van Kooten and Johnston (2013), UNECE (2012)

[1] Calculated by the author based on proportion of coniferous sawlogs + veneer logs out of total sawlogs + veneer logs multiplied by total plywood + veneer production from FAOSTAT - Forestry database

[2] Calculated by the author based on proportion of coniferous pulpwood out of total pulpwood multipled by total pulp production within a given country from FAOSTAT - Forestry database.

[3] Calculated by the author based on the proportion of coniferous industrial roundwood out of total industrial roundwood production within the given country from FAOSTAT - Forestry database.

Table A-3: Global Coniferous Forest Product Prices in 2011, $USD

Country/Region	Industrial Roundwood ('000 $/m^3)	Sawlogs + Veneer Logs ('000 $/m^3)	Pulpwood ('000 $/m^3)	Sawnwood ('000 $/m^3)	Plywood + Veneer ('000 $/m^3)	Particleboard ('000 $/m^3)	Fibreboard ('000 $/m^3)	Pulp[1] ('000 $/Mt)	Wood Pellets ('000 $/Mt)
Australia	98,153	78,304	27,037	217,213	505,570	344,480	371,493	823,264	156,803
BC Coast	105,092	98,230	33,917	198,100	510,286	301,707	431,781	636,171	126,720
BC Interior	86,000	85,418	29,493	172,262	417,584	246,897	353,341	635,890	125,440
Alberta	99,408	85,856	29,644	173,146	482,686	285,388	408,427	735,026	129,280
Atlantic Canada	108,285	94,003	32,457	189,576	525,788	310,872	444,898	800,661	158,355
Rest of Canada	103,845	98,704	34,080	199,055	504,231	298,127	426,657	767,834	153,698
Chile	98,153	78,304	27,037	186,428	433,917	295,658	371,493	697,743	152,145
China	106,333	84,829	29,290	220,770	536,000	344,500	498,000	669,668	153,698
Finland	118,230	95,780	33,071	239,890	476,320	259,090	426,790	688,375	156,803
Japan	115,875	92,442	31,918	211,007	491,125	334,638	438,568	581,117	156,803
New Zealand	98,153	78,304	27,037	186,428	433,917	295,658	371,493	577,564	153,698
Russia	91,940	88,660	30,612	186,428	335,000	176,030	324,750	594,218	153,698
Sweden	87,360	93,367	32,237	237,310	605,960	500,000	697,680	741,613	158,355
US North	153,502	115,000	39,707	275,000	526,350	471,807	295,257	623,257	166,600
US South	137,162	110,000	37,980	255,000	470,322	421,585	263,828	631,074	152,510
US West	153,721	125,000	43,160	265,000	527,101	472,479	295,678	707,259	129,280
Rest of Latin America	98,153	78,304	27,037	199,977	465,452	317,145	371,493	669,497	156,803
Rest of Europe	92,132	73,500	25,378	168,120	663,000	301,000	455,000	692,209	153,698
Rest of Asia	110,422	88,092	30,416	226,027	526,086	358,459	417,930	533,782	153,698
Rest of World	78,030	62,250	21,493	203,771	474,283	323,162	295,329	660,012	158,355

Source: FAO (2012), BC Statistics (2013), Government of Canada (2012), Oswalt et al. (2009), van Kooten and Johnston (2013), UNECE (2012), UNECE/FAO TIMBER database

[1] Calculated by the author based on a weighted average composite of regional prices for mechanical, chemical, and semi-chemical pulp prices.

Table A-4: Global Coniferous Forest Product Manufacturing Cost in 2011, $USD

Country/Region	Sawnwood ('000 $/m^3)	Plywood + Veneer ('000 $/m^3)	Particleboard ('000 $/m^3)	Fibreboard ('000 $/m^3)	Pulp ('000 $/Mt)	Wood Pellets ('000 $/Mt)
Australia	170,124	214,419	125,989	216,645	308,247	106,519
BC Coast	94,047	240,262	140,895	233,902	388,527	105,454
BC Interior	81,780	225,168	137,850	225,151	317,945	97,378
Alberta	82,200	225,685	141,866	240,578	367,513	101,050
Atlantic Canada	90,000	242,858	147,715	261,269	400,330	107,804
Rest of Canada	94,500	244,716	145,032	249,785	383,917	106,926
Chile	111,704	214,419	125,989	216,645	308,247	100,519
China	167,691	232,287	136,488	234,699	333,934	98,979
Finland	88,181	262,273	154,108	264,996	376,775	113,011
Japan	152,871	253,133	148,737	255,761	363,902	106,015
New Zealand	127,375	214,419	125,989	216,645	308,247	104,519
Russia	108,459	242,776	142,652	245,297	297,695	94,891
Sweden	54,655	255,664	150,225	258,319	405,435	102,953
US North	146,322	263,915	148,905	260,916	353,126	134,000
US South	146,322	258,025	147,716	257,500	315,537	116,000
US West	146,402	275,696	151,281	267,746	353,630	126,000
Rest of Latin America	93,659	214,419	125,989	216,645	308,247	98,519
Rest of Europe	134,956	201,264	118,260	203,354	377,500	104,972
Rest of Asia	167,691	241,221	141,738	243,726	346,778	101,709
Rest of World	119,134	170,458	100,159	172,228	245,050	91,007

Source: FAO (2012), BC Statistics (2013), Government of Canada (2012), Oswalt et al. (2009), van Kooten and Johnston (2013), UNECE (2012), as well as calculations from the author.

Table A-5: Global Coniferous Forest Product Domestic Price Elasticity of Demand

Country/Region	Sawnwood	Plywood + Veneer	Particleboard	Fibreboard	Pulp	Wood Pellets
Australia	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
BC Coast	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
BC Interior	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
Alberta	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
Atlantic Canada	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
Rest of Canada	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
Chile	-0.21	-0.59	-0.43	-0.71	-0.34	-1.10
China	-0.21	-0.59	-0.43	-0.71	-0.34	-1.10
Finland	-0.17	-0.37	-0.43	-0.58	-0.34	-1.10
Japan	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
New Zealand	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
Russia	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
Sweden	-0.17	-0.37	-0.43	-0.58	-0.34	-1.10
US North	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
US South	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
US West	-0.17	-0.59	-0.43	-0.71	-0.34	-1.10
Rest of Latin America	-0.56	-0.59	-0.43	-0.71	-0.34	-1.10
Rest of Europe	-0.17	-0.56	-0.36	-0.63	-0.34	-1.10
Rest of Asia	-0.21	-0.59	-0.43	-0.71	-0.34	-1.10
Rest of World	-0.20	-0.59	-0.43	-0.71	-0.34	-1.10

Source: van Kooten and Johnston (2013), UNECE (2012)

Table A.6: Inter-regional Transportation Costs, Twenty Regions, $\$/m^3$, 2011[a]

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	0.0	60.6	62.3	63.9	75.5	81.6	55.0	43.4	75.7	38.0	10.5	70.3	73.7	77.6	67.0	58.5	64.8	78.0	43.4	53.4
BC Coast	60.6	0.0	9.6	12.8	43.7	33.3	51.2	40.6	73.1	39.6	55.1	81.8	72.1	38.6	31.6	17.5	53.6	72.1	40.6	79.8
BC Interior	62.3	9.6	0.0	6.6	40.4	30.1	60.6	49.6	82.3	48.3	63.1	90.0	81.1	35.5	29.9	18.4	60.5	81.1	49.6	88.1
Alberta	63.9	12.8	6.6	0.0	37.1	27.0	63.2	52.6	85.2	52.0	67.1	94.0	84.1	32.3	28.1	19.3	65.3	84.1	52.5	94.5
Atlantic Canada	75.5	43.7	40.4	37.1	0.0	12.9	42.3	82.3	38.5	78.5	73.4	46.8	34.5	9.8	32.1	46.9	37.7	43.2	64.4	58.3
Rest of Canada	81.6	33.3	30.1	27.0	12.9	0.0	51.8	94.9	40.8	90.1	85.4	58.8	46.5	6.0	21.0	34.6	49.7	54.8	76.4	72.6
Chile	55.0	51.2	60.6	63.2	42.3	51.8	0.0	49.5	65.4	50.0	46.9	68.5	63.5	43.7	36.4	40.1	21.5	60.5	49.0	68.5
China	43.4	40.6	49.6	52.6	82.3	94.9	49.5	0.0	100.2	8.2	50.5	52.7	96.1	94.7	78.5	56.5	85.4	97.2	3.0	62.8
Finland	75.7	73.1	82.3	85.2	38.5	40.8	65.4	100.2	0.0	92.2	80.8	8.4	4.0	43.2	41.2	65.2	54.8	12.0	99.0	50.8
Japan	38.0	39.6	48.3	52.0	78.5	90.1	50.0	8.2	92.2	0.0	42.9	56.7	95.0	88.7	77.6	64.5	72.9	96.2	10.2	71.5
New Zealand	10.5	55.1	63.1	67.1	73.4	85.4	46.9	50.5	80.8	42.9	0.0	78.6	82.5	78.9	68.8	66.9	68.3	86.6	50.5	57.1
Russian Fed	70.3	81.8	90.0	94.0	46.8	58.8	68.5	52.7	8.4	56.7	78.6	0.0	11.3	48.2	48.2	69.3	57.2	15.2	22.2	69.2
Sweden	73.7	72.1	81.1	84.1	34.5	46.5	63.5	96.1	4.0	95.0	82.5	11.3	0.0	43.2	41.2	64.3	53.0	9.8	98.0	50.3
US North	77.6	38.6	35.5	32.3	9.8	6.0	43.7	94.7	43.2	88.7	78.9	48.2	43.2	0.0	22.8	38.9	44.7	48.9	73.0	60.9
US South	67.0	31.6	29.9	28.1	32.1	21.0	36.4	78.5	43.2	77.6	68.8	48.2	41.2	22.8	0.0	22.1	38.3	43.9	67.2	47.0
US West	58.5	17.5	18.4	19.3	46.9	34.6	40.1	56.5	65.2	64.5	66.9	69.3	64.3	38.9	22.1	0.0	48.1	68.0	44.8	77.9
Rest LA	64.8	53.6	60.5	65.3	37.7	49.7	21.5	85.4	54.8	72.9	68.3	57.2	53.0	44.7	38.3	48.1	0.0	49.2	57.4	45.8
Rest Europe	78.0	72.1	81.1	84.1	43.2	54.8	60.5	97.2	12.0	96.2	86.6	15.2	9.8	48.9	43.9	68.0	49.2	0.0	98.0	48.2
Rest Asia	43.4	40.6	49.6	52.5	64.4	76.4	49.0	3.0	99.0	10.2	50.5	22.2	98.0	73.0	67.2	44.8	57.4	98.0	0.0	62.8
ROW	53.4	79.8	88.1	94.5	58.3	72.6	68.5	62.8	50.8	71.5	57.1	69.2	50.3	60.9	47.0	77.9	45.8	48.2	62.8	0.0

[a] Calculated by the author using data from Abbott et al. (2009) and internet sources.

Table A-7: Bilateral Coniferous Industrial Roundwood Trade Flows, Twenty Model Regions, (‘000 m^3) 2011

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW	TOTAL Production
Australia	13,267.9	0.0	0.0	0.0	0.0	0.0	0.0	935.0	0.0	2.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.0	253.5	23.0	14,483.0
BC Coast	0.0	11,559.8	0.0	0.0	0.0	0.0	0.0	1,680.0	0.0	1,142.0	0.0	0.0	0.0	788.7	0.0	0.0	0.0	0.0	132.0	8.8	15,311.3
BC Interior	0.0	0.0	44,620.8	300.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44,920.8
Alberta	0.0	0.0	0.0	12,971.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	89.6	5.8	13,067.3
Atlantic Canada	0.0	0.0	0.0	0.0	11,152.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11,152.2
Rest of Canada	0.0	0.0	0.0	0.0	0.0	27,346.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	188.9	12.3	27,548.7
Chile	0.0	0.0	0.0	0.0	0.0	0.0	22,905.9	30.0	0.0	22.3	0.0	0.0	0.0	0.0	0.0	0.0	49.0	0.0	0.0	0.0	23,007.2
China	3.4	0.0	0.0	0.0	0.0	0.0	0.0	65,411.4	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	39.0	24.7	65,479.6
Finland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	38,309.4	1.0	0.0	0.0	290.0	0.0	0.0	0.0	0.0	0.0	0.0	7.6	38,609.0
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.4	0.0	14,749.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.6	0.1	14,827.0
New Zealand	17.1	0.0	0.0	0.0	0.0	0.0	4.8	2,298.0	0.0	737.0	14,713.8	0.0	0.0	0.0	0.0	0.0	0.0	1.4	3,720.9	64.5	21,557.4
Russian Fed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13,203.0	1,324.0	437.0	0.0	65,729.9	57.0	0.0	0.0	0.0	0.0	492.1	8,508.6	3,094.8	92,846.3
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	110.0	0.6	0.0	0.0	59,419.0	0.0	0.0	0.0	0.0	1,114.8	0.0	22.1	60,667.6
US North	0.0	0.0	0.0	0.0	63.7	141.5	0.0	0.0	0.0	115.2	0.6	0.1	0.0	13,220.3	0.0	0.0	15.5	26.9	108.3	14.4	13,706.6
US South	0.0	0.0	0.0	0.0	0.0	1,905.7	0.0	0.0	0.3	1,070.1	0.0	1.1	0.1	0.0	122,774.1	0.0	144.2	249.4	1,006.0	134.1	127,285.0
US West	0.0	90.0	24.0	94.6	59.0	481.0	0.0	0.0	0.0	484.6	0.0	0.5	0.0	0.0	0.0	55,717.6	65.3	112.9	455.6	60.7	57,645.9
Rest LA	0.0	0.0	0.0	0.0	0.0	0.0	100.0	55.3	0.0	0.0	0.0	0.0	0.3	9.4	4.8	7.4	50,963.7	32.4	116.2	1.9	51,291.5
Rest Europe	0.0	0.0	0.0	0.0	0.0	0.0	0.0	577.0	1,196.7	30.0	6.8	28.3	3,054.4	10.1	5.2	7.9	3.9	181,710.2	305.3	1,274.3	188,210.3
Rest Asia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	200.8	0.0	12.5	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	7,716.1	50.6	7,981.0
ROW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.4	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.3	0.7	70.1	65.7	27,117.7	27,263.3
TOTAL Consumption	13,288.5	11,649.8	44,644.8	13,365.8	11,275.0	29,874.4	23,010.7	84,427.5	40,940.5	18,805.9	14,721.2	65,760.0	62,820.7	14,028.8	122,784.2	55,734.2	51,244.4	183,811.1	22,756.2	31,917.4	916,861.2

Table A-8: Bilateral Coniferous Sawlog Trade Flows, Twenty Model Regions, (‘000 m^3) 2011

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW	TOTAL Production
Australia	8,188.5	0.0	0.0	0.0	0.0	0.0	0.0	615.2	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	166.8	15.2	8,988.0
BC Coast	0.0	9,500.2	0.0	0.0	0.0	0.0	0.0	1,261.0	0.0	857.2	0.0	0.0	0.0	592.0	0.0	0.0	0.0	0.0	99.1	6.6	12,316.0
BC Interior	0.0	0.0	47,774.5	299.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48,074.0
Alberta	0.0	0.0	0.0	13,311.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	85.8	5.6	13,403.3
Atlantic Canada	0.0	0.0	0.0	0.0	9,387.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9,387.6
Rest of Canada	0.0	0.0	0.0	0.0	0.0	28,063.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	180.8	11.7	28,257.1
Chile	0.0	0.0	0.0	0.0	0.0	0.0	15,460.4	18.6	0.0	13.8	0.0	0.0	0.0	0.0	0.0	0.0	30.3	0.0	0.0	0.0	15,523.0
China	2.0	0.0	0.0	0.0	0.0	0.0	0.0	37,573.6	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.4	14.2	37,612.9
Finland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	18,613.8	0.5	0.0	0.0	144.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	18,762.6
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.0	0.0	13,809.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44.1	0.1	13,877.0
New Zealand	5.9	0.0	0.0	0.0	0.0	0.0	1.6	788.8	0.0	253.0	5,895.8	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1,277.3	22.1	8,245.0
Russian Fed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8,698.3	872.3	287.9	0.0	47,835.4	37.6	0.0	0.0	0.0	0.0	324.2	5,605.5	2,038.9	65,700.0
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	63.3	0.3	0.0	0.0	32,881.7	0.0	0.0	0.0	0.0	641.3	0.0	12.7	33,600.0
US North	0.0	0.0	0.0	0.0	37.7	83.8	0.0	0.0	0.0	68.2	0.4	0.1	0.0	8,356.7	0.0	0.0	9.2	15.9	64.2	8.5	8,644.7
US South	0.0	0.0	0.0	0.0	0.0	1,128.7	0.0	0.0	0.2	633.8	0.0	0.7	0.0	0.0	77,609.9	0.0	85.4	147.7	595.8	79.4	80,281.6
US West	0.0	53.3	14.2	56.0	34.9	284.9	0.0	0.0	0.0	287.0	0.0	0.3	0.0	0.0	0.0	35,216.7	38.7	66.9	269.8	36.0	36,358.7
Rest LA	0.0	0.0	0.0	0.0	0.0	0.0	10.2	5.6	0.0	0.0	0.0	0.0	0.0	1.0	0.5	0.8	4,975.7	3.3	11.8	0.2	5,009.0
Rest Europe	0.0	0.0	0.0	0.0	0.0	0.0	0.0	379.1	786.2	19.7	4.5	18.6	2,006.7	6.6	3.4	5.2	2.6	117,761.4	200.6	837.2	122,031.8
Rest Asia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	119.6	0.0	7.5	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	3,713.2	30.1	3,871.0
ROW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48.9	0.0	0.0	0.0	0.0	0.0	1.9	1.0	1.5	4.0	406.4	381.0	81,707.1	82,551.8
TOTAL Consumption	8,196.3	9,553.5	47,788.7	13,666.9	9,460.2	29,560.6	15,472.2	49,532.8	20,335.8	16,240.9	5,900.6	47,855.1	35,070.0	8,958.2	77,614.8	35,224.8	5,147.8	119,368.1	12,718.1	84,829.5	652,495.0

Table A-9: Bilateral Coniferous Lumber Trade Flows, Twenty Model Regions, (‘000 m^3) 2011

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW	TOTAL Production
Australia	3,738.3	0.0	0.0	0.0	0.0	0.1	0.6	42.1	0.0	4.6	2.8	0.0	0.0	0.0	0.0	0.3	0.0	0.4	36.5	0.4	3,826.0
BC Coast	7.9	56.5	55.2	217.7	135.8	1,369.1	0.6	472.3	0.2	274.9	4.0	0.0	0.4	769.3	607.2	394.3	2.2	45.1	15.7	23.0	4,451.3
BC Interior	28.2	747.5	1,653.7	781.6	487.5	2,916.4	2.2	1,695.9	0.7	987.0	14.5	0.0	1.4	2,762.6	2,180.3	1,416.0	7.9	161.8	56.5	82.5	15,984.3
Alberta	7.9	208.4	55.3	66.1	135.9	1,370.7	0.6	472.8	0.2	275.2	4.0	0.0	0.4	770.2	607.9	394.8	2.2	45.1	15.8	23.0	4,456.5
Atlantic Canada	5.5	146.0	38.7	152.6	388.9	560.0	0.4	331.2	0.1	192.7	2.8	0.0	0.3	539.5	425.8	276.5	1.6	31.6	11.0	16.1	3,121.3
Rest of Canada	16.6	439.4	116.6	459.4	286.6	2,569.7	1.3	996.8	0.4	580.2	8.5	0.0	0.8	1,623.8	1,281.6	832.3	4.7	95.1	33.2	48.5	9,395.3
Chile	17.0	0.9	0.3	1.0	0.6	6.2	4,537.4	322.0	1.5	289.0	1.5	0.0	0.0	122.5	96.7	62.8	468.3	96.3	197.6	409.2	6,630.8
China	0.7	0.0	0.0	0.0	0.0	0.0	0.0	17,800.2	0.0	77.4	0.2	0.1	0.0	0.3	0.2	0.2	2.0	4.0	21.0	11.7	17,918.0
Finland	10.0	0.0	0.0	0.0	0.0	0.2	0.0	74.0	4,652.5	623.0	0.0	0.3	9.4	0.4	0.3	0.2	0.1	2,313.5	29.8	1,986.1	9,700.0
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.5	0.0	9,277.9	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	2.1	1.2	9,294.0
New Zealand	275.0	0.0	0.0	2.0	0.0	2.0	0.1	683.0	2.4	131.0	1,665.0	0.0	0.6	82.5	65.1	42.3	0.0	107.0	326.2	549.7	3,934.0
Russian Fed	0.1	0.0	0.0	0.0	0.0	0.0	0.0	4,344.0	287.2	843.0	0.0	16,889.6	11.2	0.5	0.0	1.5	0.0	2,919.9	213.4	3,544.5	29,055.0
Sweden	26.0	2.8	0.8	3.0	1.8	18.6	0.1	72.0	25.3	743.0	0.1	0.0	5,689.3	14.3	11.3	7.3	0.1	6,902.8	15.9	2,865.3	16,400.0
US North	1.0	5.8	1.5	6.0	3.8	37.9	0.0	33.5	0.0	24.0	0.0	0.1	0.0	782.1	1,318.2	856.1	51.8	5.6	4.6	6.4	3,138.3
US South	9.6	53.5	14.2	55.9	34.9	351.6	0.1	310.8	0.1	223.0	0.2	0.6	0.4	15,510.4	3,994.1	7,950.1	480.7	51.6	43.0	59.5	29,144.3
US West	4.4	24.2	6.4	25.3	15.8	159.3	0.1	140.8	0.0	101.0	0.1	0.3	0.2	7,024.5	5,044.0	365.4	217.7	23.4	19.5	26.9	13,199.2
Rest LA	0.3	0.4	0.1	0.4	0.3	2.7	2.2	128.6	0.0	1.6	1.1	0.2	0.1	185.5	146.4	95.1	2,050.6	1.3	3.5	0.4	2,620.6
Rest Europe	245.1	0.4	0.1	0.4	0.2	2.4	0.0	215.5	66.2	881.8	0.6	6.4	144.7	64.9	51.2	33.3	32.2	71,846.7	6.4	156.3	73,754.8
Rest Asia	0.5	0.0	0.0	0.0	0.0	0.0	0.0	20.1	0.0	17.6	0.4	0.0	0.0	0.4	0.3	0.2	23.9	131.2	5,946.9	6.5	6,148.0
ROW	0.3	0.0	0.0	0.0	0.0	0.1	0.0	11.0	0.1	0.8	2.1	0.0	1.4	0.3	0.2	0.1	153.4	3,500.5	63.2	33,894.2	37,627.7
TOTAL Consumption	4,394.4	1,685.7	1,942.9	1,771.5	1,492.0	9,367.2	4,545.7	28,178.9	5,037.1	15,548.8	1,707.9	16,897.7	5,860.6	30,254.1	15,830.8	12,728.8	3,499.6	88,282.8	7,061.7	43,711.2	299,799.4

Table A-10: Bilateral Coniferous Plywood + Veneer Trade Flows, Twenty Model Regions, (‘000 m^3) 2011

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW	TOTAL Production
Australia	124.6	0.0	0.0	0.0	0.0	0.1	0.0	1.3	0.0	0.1	0.0	0.0	0.0	0.3	0.3	0.2	0.0	0.3	84.0	1.9	213.2
BC Coast	2.6	235.5	0.0	0.2	0.1	1.2	0.0	0.5	0.0	1.2	0.0	0.0	0.1	49.2	38.8	25.2	0.3	3.1	0.9	11.6	370.6
BC Interior	9.2	0.7	844.5	0.7	0.4	4.3	0.1	1.9	0.1	4.4	0.0	0.0	0.3	176.7	139.5	90.6	0.9	11.2	3.4	42.1	1,330.9
Alberta	0.4	0.0	0.0	36.1	0.0	0.2	0.0	0.1	0.0	0.2	0.0	0.0	0.0	7.8	6.2	4.0	0.0	0.5	0.2	1.8	57.5
Atlantic Canada	0.7	0.0	0.0	0.1	52.2	0.3	0.0	0.1	0.0	0.3	0.0	0.0	0.0	13.1	10.3	6.7	0.1	0.8	0.3	3.1	88.1
Rest of Canada	2.2	0.2	0.0	0.2	0.1	171.6	0.0	0.5	0.0	1.1	0.0	0.0	0.1	42.5	33.6	21.8	0.2	2.7	0.8	9.1	286.8
Chile	52.1	2.5	0.7	2.7	1.7	16.8	127.4	5.6	3.2	3.2	1.0	0.0	13.1	122.5	96.7	62.8	235.3	308.2	4.0	221.7	1,281.1
China	39.1	16.6	4.4	17.4	10.8	109.2	12.2	25,422.3	11.6	469.3	0.7	34.3	52.3	685.3	540.9	351.3	149.8	1,650.0	961.7	0.1	30,539.0
Finland	0.7	0.1	0.0	0.1	0.1	0.8	0.1	4.3	169.1	3.0	0.0	1.6	35.7	5.5	4.4	2.8	0.1	365.0	13.1	406.9	1,013.4
Japan	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	2,508.5	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	2.1	4.5	2,518.3
New Zealand	134.2	0.0	0.0	0.0	0.0	0.1	0.1	7.1	0.0	142.0	543.2	0.0	0.0	0.9	0.7	0.5	0.0	0.7	97.2	126.8	1,053.5
Russian Fed	0.7	1.1	0.3	1.1	0.7	7.1	0.0	23.9	45.7	146.7	0.0	1,417.3	16.0	49.5	39.0	25.3	1.0	406.7	11.9	604.5	2,798.7
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	57.4	0.1	0.1	0.1	3.1	36.6	0.2	14.2	112.0
US North	6.7	4.0	1.1	4.2	2.6	26.3	0.1	1.4	0.1	0.2	0.4	0.1	0.2	435.3	0.0	0.0	18.0	9.9	2.0	22.5	535.2
US South	62.0	37.2	9.9	38.9	24.2	244.4	1.0	12.6	1.2	1.9	3.5	1.4	2.1	0.0	4,042.8	0.0	167.1	92.0	18.8	209.0	4,969.9
US West	28.1	16.8	4.5	17.6	11.0	110.7	0.5	5.7	0.5	0.9	1.6	0.6	1.0	0.0	0.0	1,830.9	75.7	41.7	8.5	94.6	2,250.8
Rest LA	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.3	0.0	0.0	0.0	0.0	0.2	9.3	7.3	4.7	674.3	0.4	0.2	16.0	712.8
Rest Europe	3.3	0.6	0.2	0.6	0.4	4.0	5.1	5.5	23.1	2.4	0.0	27.8	48.4	9.9	7.8	5.1	24.9	1,017.7	14.8	2,739.7	3,941.3
Rest Asia	7.4	0.1	0.0	0.1	0.0	0.4	0.0	24.2	0.1	162.9	0.0	0.0	0.0	10.4	8.2	5.3	7.7	23.4	505.9	194.8	950.9
ROW	14.6	0.5	0.1	0.5	0.3	3.2	19.7	4.2	6.3	0.3	3.6	0.4	4.0	30.7	24.2	15.7	91.0	701.2	13.6	34,319.5	35,253.8
TOTAL Consumption	488.5	315.9	865.8	120.4	104.7	700.9	166.5	25,523.4	261.0	3,448.6	553.9	1,485.0	230.8	1,649.1	5,000.7	2,453.1	1,449.5	4,672.1	1,743.7	39,044.3	90,277.9

Table A-11:Bilateral Coniferous Particleboard (PB & OSB)Trade Flows, Twenty Model Regions, (‘000 m^3) 2011

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW	TOTAL Production
Australia	771.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	772.7
BC Coast	0.0	602.0	0.0	0.0	0.0	0.2	0.3	0.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	2.7	607.4
BC Interior	0.1	0.1	2,161.8	0.1	0.1	0.6	1.0	3.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	4.0	0.0	9.6	2,180.9
Alberta	0.0	0.0	0.0	875.2	0.0	0.2	0.4	1.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	3.9	883.0
Atlantic Canada	0.0	0.0	0.0	0.0	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6
Rest of Canada	0.1	0.1	0.0	0.1	0.1	2,597.1	1.4	4.1	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	5.3	0.0	12.2	2,621.4
Chile	0.1	0.0	0.0	0.0	0.0	0.0	461.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.6	22.5	0.1	29.9	520.7
China	0.7	0.0	0.0	0.0	0.0	0.2	0.9	8,008.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	22.6	1.5	143.8	8,180.4
Finland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	139.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6	0.0	11.6	163.0
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.5	0.0	32.5	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	421.8	488.4	948.6
New Zealand	23.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	103.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.8	144.6
Russian Fed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.3	0.0	0.0	0.0	4,997.1	0.0	0.0	0.0	0.0	0.0	65.8	0.2	123.9	5,204.3
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	476.0	0.0	0.0	0.0	0.0	16.1	0.0	13.2	507.1
US North	0.0	1.9	0.5	1.9	1.2	12.2	0.7	0.3	0.0	0.0	0.0	0.0	0.0	782.8	0.0	0.0	0.2	2.7	0.1	1.0	805.6
US South	0.0	17.3	4.6	18.1	11.3	113.7	6.8	3.1	0.0	0.0	0.0	0.1	0.0	0.0	7,269.8	0.0	1.9	25.3	0.6	9.1	7,481.6
US West	0.0	7.8	2.1	8.2	5.1	51.5	3.1	1.4	0.0	0.0	0.0	0.1	0.0	0.0	0.0	3,292.4	0.9	11.4	0.3	4.1	3,388.3
Rest LA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	102.5	0.0	0.0	0.0	0.0	0.0	0.0	265.7	19.3	0.0	22.6	410.3
Rest Europe	15.0	0.4	0.1	0.4	0.3	2.5	18.2	81.2	80.5	38.5	0.0	135.8	249.2	14.4	11.4	7.4	13.1	26,010.7	110.0	4,780.6	31,569.5
Rest Asia	0.1	0.0	0.0	0.0	0.0	0.1	0.0	22.4	0.0	0.0	0.0	0.1	1.4	0.0	0.0	0.0	0.2	13.4	163.5	41.9	243.1
ROW	0.0	0.0	0.0	0.0	0.0	0.0	44.5	19.8	0.0	210.3	0.2	149.2	64.4	801.2	632.3	410.7	125.8	944.7	199.7	10,695.6	14,298.4
TOTAL Consumption	811.4	629.7	2,169.1	904.1	22.6	2,778.5	538.7	8,168.6	223.8	383.8	103.5	5,282.4	791.0	1,598.6	7,913.6	3,710.5	416.8	27,178.3	897.6	16,412.8	80,935.5

Table A-12: Bilateral Coniferous Fibreboard (MDF) Trade Flows, Twenty Model Regions, (‘000 m^3) 2011

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW	TOTAL Production
Australia	126.1	0.4	0.1	0.4	0.3	2.5	0.0	56.0	0.0	0.0	0.0	2.9	1.5	9.8	7.7	5.0	1.5	57.7	17.7	184.5	474.1
BC Coast	0.0	110.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.6	111.2
BC Interior	0.0	0.0	394.9	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.7	0.0	2.2	399.3
Alberta	0.0	0.0	0.0	157.3	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.7	0.0	2.2	161.7
Atlantic Canada	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.8
Rest of Canada	0.1	0.2	0.1	0.2	0.1	432.3	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	19.8	0.0	23.7	480.0
Chile	0.1	4.2	1.1	4.4	2.7	27.6	756.2	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.2	11.5	0.9	100.7	957.6
China	22.0	6.8	1.8	7.2	4.5	45.0	9.8	29,743.0	0.2	2.6	0.0	0.6	0.6	350.0	124.0	36.0	16.8	20.4	201.7	982.1	31,575.2
Finland	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	88.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.1	3.7	95.9
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	0.0	226.5	0.0	9.9	0.0	0.0	0.0	0.0	1.0	13.1	4.7	565.2	824.9
New Zealand	22.8	0.3	0.1	0.3	0.2	2.0	0.0	90.1	0.0	0.0	290.3	0.0	0.0	0.0	0.0	0.0	6.9	0.1	69.2	191.7	674.3
Russian Fed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	1,402.4	0.0	0.0	0.0	0.0	0.0	52.0	0.3	32.6	1,490.6
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	5.4	0.0	0.0	0.0	30.0	0.0	0.0	0.0	0.2	15.5	1.3	43.6	96.5
US North	0.4	2.2	0.6	2.3	1.4	14.2	0.1	0.3	0.1	0.0	0.0	0.0	0.2	376.7	0.0	0.0	0.4	1.5	0.1	15.3	415.7
US South	4.2	20.0	5.3	20.9	13.0	131.6	0.8	3.1	0.6	0.0	0.0	0.0	2.2	0.1	3,497.9	0.0	3.4	14.3	1.0	141.8	3,860.3
US West	1.9	9.1	2.4	9.5	5.9	59.6	0.4	1.4	0.3	0.0	0.0	0.0	1.0	0.0	0.0	1,584.1	1.6	6.5	0.5	64.2	1,748.3
Rest LA	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	2.9	0.0	25.8	32.9	1.4	1.1	0.7	31.2	21.0	2.2	0.0	119.8
Rest Europe	18.6	10.8	2.9	11.3	7.1	71.2	45.2	37.5	108.1	300.7	0.4	136.8	169.7	67.2	53.1	34.5	32.4	6,174.3	307.9	5,345.5	12,935.1
Rest Asia	2.3	0.0	0.0	0.0	0.0	0.1	0.0	8.7	0.0	0.0	0.0	0.4	1.4	0.0	0.0	0.0	0.2	4.8	415.5	1.9	435.5
ROW	6.0	1.7	0.4	1.7	1.1	10.9	11.6	6.9	0.4	29.3	0.5	170.5	19.6	431.9	340.9	221.4	702.8	613.3	230.4	35,285.1	38,086.6
TOTAL Consumption	204.8	165.7	409.7	215.6	36.5	797.6	824.5	29,956.8	206.8	562.1	291.2	1,749.4	259.2	1,237.1	4,024.7	1,881.8	846.5	7,033.1	1,253.7	42,986.5	94,943.4

Table A-13: Bilateral Coniferous Pulp Trade Flows, Twenty Model Regions, (‘000 Mt) 2011

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW	TOTAL Production
Australia	477.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.5	0.0	0.1	12.5	491.2
BC Coast	3.1	1,319.4	0.0	0.0	0.0	0.0	0.0	129.4	0.1	26.1	0.0	0.2	178.2	1.3	1.0	0.7	9.2	2.9	47.3	196.3	1,915.2
BC Interior	11.2	0.0	4,738.0	0.0	0.0	0.0	0.0	464.6	0.4	93.8	0.0	0.7	639.9	4.6	3.7	2.4	33.1	10.3	169.8	704.9	6,877.5
Alberta	6.9	0.0	0.0	1,102.1	0.0	0.0	0.0	285.3	0.2	57.6	0.0	0.4	293.0	2.8	2.2	1.5	20.3	6.3	44.3	94.5	1,917.5
Atlantic Canada	3.5	0.0	0.0	0.0	43.7	0.0	0.0	145.4	0.1	29.4	0.0	0.2	150.3	1.5	1.1	0.7	10.4	3.2	53.1	31.2	474.0
Rest of Canada	9.0	0.0	0.0	0.0	0.0	169.2	0.0	371.0	0.3	74.9	0.0	0.6	511.1	3.7	2.9	1.9	26.5	8.2	135.6	111.8	1,426.7
Chile	10.6	0.1	0.0	0.1	0.0	0.3	413.6	576.0	5.1	37.5	0.5	11.1	11.7	0.8	0.6	0.4	47.1	34.2	557.3	418.3	2,125.4
China	0.1	0.0	0.0	0.0	0.0	0.0	0.0	6,298.2	2.2	0.0	0.0	0.0	0.0	0.3	0.2	0.1	2.9	0.2	1.3	34.9	6,340.5
Finland	0.0	0.0	0.0	0.0	0.0	0.1	0.0	322.0	5,684.6	20.2	14.1	74.8	3.5	32.3	25.5	16.5	119.0	2.9	1,382.6	114.2	7,812.3
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	159.9	0.0	3,843.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	55.4	4,058.6
New Zealand	88.2	0.0	0.0	0.0	0.0	0.0	0.0	254.2	0.0	209.0	611.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.8	260.9	1,431.9
Russian Fed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	841.0	14.5	73.3	0.0	3,706.0	6.8	15.1	11.9	7.8	50.3	48.9	437.3	54.4	5,267.4
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	180.2	50.7	29.0	1.1	0.0	6,983.8	16.1	12.7	8.3	85.8	65.9	2,727.4	180.5	10,341.6
US North	0.3	0.7	0.2	0.8	0.5	4.9	1.3	65.8	0.0	20.6	1.3	2.4	0.0	123.2	4.0	2.6	22.7	37.0	74.9	1,529.5	1,892.6
US South	3.2	6.9	1.8	7.2	4.5	45.6	11.9	845.0	0.4	191.4	12.1	22.6	0.0	46.8	12,623.7	24.0	210.5	343.3	870.4	2,305.4	17,576.5
US West	1.5	3.1	0.8	3.3	2.0	20.6	5.4	382.7	0.2	86.7	5.5	10.2	0.0	21.2	16.7	4,783.5	95.3	155.5	394.2	1,971.9	7,960.2
Rest LA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rest Europe	0.8	0.0	0.0	0.0	0.0	0.2	0.0	545.4	67.0	41.9	4.5	225.1	17.0	22.7	17.9	11.6	184.6	4,875.2	4,300.0	85.2	10,399.2
Rest Asia	0.1	0.0	0.0	0.0	0.0	0.0	0.0	78.5	0.0	9.1	0.0	0.0	0.5	0.1	0.1	0.1	1.8	0.0	276.1	72.7	439.2
ROW	37.9	4.9	1.3	5.1	3.2	32.1	1.4	1,678.5	196.5	166.1	9.3	20.2	139.5	16.5	13.0	8.5	58.6	94.0	1,573.0	2,235.1	6,294.6
TOTAL Consumption	653.5	1,335.2	4,742.2	1,118.6	54.0	273.0	433.6	13,623.9	6,022.3	5,010.0	660.4	4,074.7	8,935.4	309.0	12,737.4	4,870.5	978.6	5,688.1	13,052.3	10,469.6	95,042.2

Addendum B – Shadow Prices on Calibration Constraint

Table B-1: Adjustments required to the Transaction Cost Matrix for Industrial Roundwood, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	-176.5	-253.5	-255.5	-257.6	-272.4	-280.1	-246.4	-231.6	-272.6	-224.7	-189.7	-265.8	-270.1	-275.0	-261.6	-250.8	-258.8	-275.6	-231.6	-244.3
BC Coast	-222.2	-145.2	-157.4	-161.5	-200.7	-187.4	-210.2	-196.8	-238.0	-195.5	-215.1	-249.0	-236.8	-194.2	-185.3	-167.4	-213.2	-236.8	-196.8	-246.5
BC Interior	-195.1	-128.3	-116.1	-124.5	-167.4	-154.3	-193.0	-179.1	-220.6	-177.4	-196.2	-230.4	-219.1	-161.1	-154.0	-139.4	-192.8	-219.1	-179.0	-228.0
Alberta	-213.6	-148.8	-140.9	-132.5	-179.6	-166.7	-212.7	-199.3	-240.7	-198.5	-217.7	-251.9	-239.3	-173.5	-168.2	-157.0	-215.4	-239.3	-199.2	-252.5
Atlantic Canada	-240.5	-200.1	-196.0	-191.8	-144.6	-161.0	-198.3	-249.1	-193.4	-244.3	-237.8	-204.1	-188.4	-157.1	-185.4	-204.1	-192.5	-199.5	-226.4	-218.6
Rest of Canada	-241.2	-179.8	-175.8	-171.8	-153.9	-137.6	-203.4	-258.1	-189.4	-252.0	-246.0	-212.3	-196.6	-145.1	-164.2	-181.5	-200.7	-207.2	-234.6	-229.7
Chile	-269.6	-264.7	-276.7	-280.0	-253.4	-265.5	-193.5	-262.6	-282.8	-263.2	-259.3	-286.8	-280.3	-255.2	-245.9	-250.6	-227.0	-276.6	-262.0	-286.7
China	-254.2	-250.6	-262.1	-265.9	-303.5	-319.6	-261.9	-199.0	-326.2	-209.4	-263.1	-265.9	-321.1	-319.2	-298.7	-270.7	-307.4	-322.4	-202.8	-278.8
Finland	-387.4	-384.2	-395.9	-399.5	-340.1	-343.2	-374.4	-418.5	-291.3	-408.3	-393.9	-302.0	-296.4	-346.2	-343.6	-374.2	-360.9	-306.5	-417.0	-355.9
Japan	-258.4	-260.5	-271.5	-276.2	-309.9	-324.6	-273.6	-220.6	-327.2	-210.2	-264.6	-282.1	-330.8	-322.7	-308.7	-292.0	-302.7	-332.3	-223.1	-300.9
New Zealand	-190.9	-247.6	-257.7	-262.8	-270.8	-286.0	-237.2	-241.7	-280.2	-232.1	-177.6	-277.4	-282.4	-277.8	-265.0	-262.6	-264.4	-287.7	-241.7	-250.1
Russian Fed	-285.0	-299.6	-310.0	-315.1	-255.2	-270.4	-282.7	-262.6	-206.4	-267.7	-295.5	-173.5	-210.1	-256.9	-256.9	-283.7	-268.4	-215.0	-223.8	-283.5
Sweden	-310.5	-308.4	-319.9	-323.7	-260.6	-275.8	-297.4	-338.9	-221.9	-337.5	-321.6	-231.2	-216.8	-271.7	-269.1	-298.4	-284.1	-229.3	-341.3	-280.7
US North	-387.4	-337.9	-333.9	-329.9	-301.4	-296.5	-344.3	-409.1	-343.7	-401.5	-389.0	-350.1	-343.7	-288.9	-317.9	-338.4	-345.7	-351.0	-381.6	-366.3
US South	-342.8	-297.8	-295.6	-293.4	-298.4	-284.3	-303.8	-357.4	-312.5	-356.2	-345.1	-318.8	-310.0	-286.7	-257.7	-285.7	-306.3	-313.4	-343.0	-317.3
US West	-374.1	-321.9	-323.1	-324.3	-359.3	-343.7	-350.6	-371.4	-382.6	-381.6	-384.7	-387.7	-381.3	-349.2	-327.8	-299.7	-360.8	-386.0	-356.7	-398.6
Rest LA	-229.9	-215.7	-224.4	-230.6	-195.5	-210.7	-174.9	-256.0	-217.2	-240.2	-234.4	-220.3	-214.9	-204.4	-196.2	-208.7	-147.6	-210.1	-220.4	-205.7
Rest Europe	-267.5	-260.0	-271.4	-275.2	-223.2	-238.0	-245.2	-291.7	-183.6	-290.5	-278.4	-187.6	-180.8	-230.4	-224.1	-254.7	-230.9	-168.4	-292.8	-229.5
Rest Asia	-337.5	-334.0	-345.4	-349.1	-364.1	-379.4	-344.6	-286.2	-408.1	-295.3	-346.5	-310.5	-406.9	-375.1	-367.7	-339.3	-355.2	-406.9	-282.4	-362.2
ROW	-194.8	-228.3	-238.9	-247.0	-201.0	-219.1	-214.0	-206.8	-191.5	-217.8	-199.5	-214.8	-190.9	-204.4	-186.6	-225.9	-185.1	-188.2	-206.8	-127.0

Table B-2: Adjustments required to the Transaction Cost Matrix for Lumber, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	-6.8	-86.6	-114.0	-114.8	-109.9	-106.5	-110.0	-46.7	-62.0	-55.3	-58.9	-129.6	-62.6	-26.6	-36.0	-17.6	-88.8	-133.9	-41.4	-73.7
BC Coast	-7.1	44.4	8.9	6.6	-7.9	12.1	-34.3	26.4	11.1	13.7	-32.3	-68.9	9.5	53.0	40.0	64.1	-7.4	-57.7	31.7	-29.7
BC Interior	16.5	58.6	42.4	36.6	19.3	39.1	-17.8	41.3	26.0	29.4	-15.1	-50.7	24.6	83.8	69.4	90.9	9.7	-42.9	46.6	-14.2
Alberta	8.7	49.3	29.7	37.2	16.5	36.2	-26.6	32.2	17.0	19.6	-25.3	-60.8	15.5	67.8	51.9	70.8	-1.3	-52.0	37.5	-26.7
Atlantic Canada	-23.9	-1.8	-24.3	-20.2	33.4	30.0	-27.2	-17.7	43.4	-27.5	-52.6	-35.5	44.8	109.0	66.7	61.9	6.1	-31.2	5.5	-10.7
Rest of Canada	-24.7	14.5	-8.2	-4.2	26.3	48.7	-31.7	-24.5	46.7	-33.4	-59.2	-42.7	38.5	108.7	73.7	70.1	-0.1	-37.1	-0.7	-19.2
Chile	-18.6	-24.6	-59.9	-61.5	-24.2	-24.3	14.9	-0.2	1.1	-14.2	-41.3	-72.2	0.5	59.8	47.1	53.4	7.0	-63.9	5.5	-51.2
China	-42.7	-48.0	-82.9	-85.0	-98.2	-101.4	-86.2	15.3	-68.0	-7.1	-80.6	-93.8	-66.5	-25.1	-29.0	3.1	-90.9	-134.5	17.5	-64.6
Finland	-29.6	-34.1	-69.2	-71.2	-8.0	-0.9	-57.3	-38.5	80.8	-45.1	-65.5	-5.1	71.8	72.7	54.7	40.6	-14.0	-3.0	-32.1	-6.2
Japan	-29.2	-39.4	-74.0	-76.8	-86.9	-88.9	-78.3	14.7	-52.3	13.1	-64.9	-89.3	-57.7	-11.6	-20.5	2.6	-70.8	-125.9	17.9	-65.6
New Zealand	13.4	-41.0	-74.8	-78.0	-67.8	-70.3	-59.4	-13.7	-26.8	-19.6	2.4	-94.8	-31.1	12.1	2.1	14.1	-52.4	-102.5	-8.5	-37.4
Russian Fed	-34.0	-55.3	-89.3	-92.5	-28.9	-31.4	-68.6	-3.5	58.0	-21.0	-73.1	14.8	52.5	55.2	35.2	24.1	-28.9	-18.7	32.3	-83.6
Sweden	18.7	13.1	-21.7	-23.9	42.2	39.7	-8.9	11.8	120.6	-1.6	-20.8	38.5	124.4	118.9	100.9	87.9	34.1	45.4	15.1	40.6
US North	-112.7	-79.1	-101.8	-97.8	-58.9	-45.6	-117.9	-112.5	-44.7	-121.8	-144.8	-127.9	-47.3	36.4	-6.5	-12.6	-83.4	-119.4	-85.6	-95.8
US South	-90.9	-61.8	-85.9	-83.3	-70.8	-50.3	-98.7	-86.1	-34.2	-100.0	-123.5	-115.6	-34.8	23.8	26.7	14.6	-66.6	-104.1	-69.5	-71.5
US West	-103.6	-68.4	-95.1	-95.2	-106.3	-84.5	-123.8	-84.7	-77.0	-107.7	-142.7	-158.3	-78.6	-12.9	-16.1	16.0	-97.1	-148.8	-67.8	-123.1
Rest LA	-5.3	-3.2	-35.9	-39.9	4.2	1.6	1.3	-12.3	35.4	-13.6	-39.6	-38.5	34.6	82.6	69.0	69.2	52.3	-28.8	21.0	10.3
Rest Europe	-55.3	-60.1	-95.0	-97.1	-39.7	-41.9	-73.6	-62.5	40.1	-74.6	-94.7	-31.7	39.7	40.0	25.0	10.9	-35.4	-18.0	-58.1	-30.5
Rest Asia	-47.5	-52.6	-87.4	-89.4	-84.8	-87.4	-90.7	7.7	-71.4	-13.7	-85.4	-68.4	-73.0	-8.1	-22.2	10.1	-67.4	-139.9	16.0	-69.1
ROW	20.1	-15.1	-49.3	-54.8	-2.2	-7.0	-31.9	24.5	53.6	2.0	-14.3	-36.6	51.5	80.6	74.6	53.7	20.7	-13.5	29.7	70.3

Table B-3: Adjustments required to the Transaction Cost Matrix for Plywood + Veneer, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	237.5	141.6	77.3	100.8	122.3	114.6	110.9	224.6	174.6	185.1	155.4	40.3	264.2	180.8	200.2	200.5	132.6	317.0	214.7	152.8
BC Coast	146.6	171.9	99.6	121.5	123.7	132.6	84.4	197.0	146.8	153.1	80.5	-1.5	235.5	189.4	205.3	211.3	113.5	292.5	187.1	96.2
BC Interior	170.9	188.2	135.1	153.6	152.9	161.7	100.9	213.9	163.5	170.4	98.4	16.2	252.4	218.5	232.9	236.3	132.6	309.4	204.0	113.7
Alberta	162.0	177.8	121.3	153.0	149.0	157.6	91.1	203.7	153.4	159.5	87.1	5.0	242.2	214.4	227.4	228.1	120.5	299.2	193.9	100.1
Atlantic Canada	125.7	122.2	62.8	91.1	161.4	147.0	87.3	149.3	175.5	108.2	56.1	27.4	267.1	212.1	198.7	175.8	123.3	315.4	157.3	111.6
Rest of Canada	123.0	136.0	76.5	104.7	151.9	163.2	81.1	140.1	176.5	100.0	47.5	18.8	258.5	219.4	213.2	191.5	114.7	307.1	148.7	100.7
Chile	180.4	149.0	76.8	99.4	153.4	142.3	163.8	216.4	182.8	171.0	116.9	40.0	272.4	212.6	228.7	216.9	173.9	332.4	207.0	135.6
China	179.2	146.7	74.9	97.1	100.5	86.3	101.4	253.0	135.2	199.9	100.4	43.0	226.9	148.7	173.7	187.6	97.1	282.8	240.1	128.4
Finland	100.9	68.2	-3.7	18.5	98.4	94.4	39.5	106.9	189.3	70.0	24.1	41.3	273.0	154.2	165.0	132.9	81.6	322.0	98.1	94.5
Japan	157.8	120.9	49.5	70.9	77.5	64.4	74.2	218.0	116.4	181.3	81.3	12.2	201.2	127.9	147.8	152.9	82.8	257.1	206.1	93.0
New Zealand	226.1	146.2	75.5	96.6	123.4	109.9	118.0	216.5	168.5	179.2	164.9	31.0	254.4	178.5	197.4	191.2	128.1	307.4	206.6	148.2
Russian Fed	134.8	88.0	17.1	38.2	118.5	104.9	64.9	182.9	209.5	134.0	54.9	78.2	294.2	177.7	186.6	157.4	107.7	347.3	203.5	104.7
Sweden	120.2	86.5	14.8	36.9	119.7	106.1	58.8	128.3	202.7	84.5	39.8	55.7	294.3	171.5	182.4	151.2	100.8	341.5	116.4	112.3
US North	77.4	81.1	21.5	49.8	105.3	107.7	39.7	90.7	124.5	51.9	4.4	-20.2	212.2	175.7	161.8	137.5	70.1	263.5	102.4	62.7
US South	103.2	103.4	42.4	69.2	98.4	107.9	62.2	122.2	139.8	78.2	29.8	-4.9	229.5	168.2	199.9	169.7	91.9	283.8	123.6	92.0
US West	80.9	86.7	23.0	47.2	52.8	63.5	27.7	113.4	86.9	60.5	0.9	-56.8	175.6	121.3	147.0	161.0	51.3	228.9	115.1	30.3
Rest LA	172.7	148.6	79.0	99.3	160.0	146.4	144.4	182.6	195.4	150.2	97.5	53.3	284.9	213.6	228.9	211.0	197.4	345.7	200.7	160.4
Rest Europe	175.8	146.4	74.7	96.8	170.8	157.6	121.6	187.1	254.5	143.2	95.5	111.7	344.4	225.7	239.6	207.4	164.5	411.2	176.3	174.3
Rest Asia	167.2	134.7	63.0	85.2	106.4	92.9	89.9	238.0	124.3	186.0	88.4	61.5	213.0	158.3	173.0	187.3	113.1	270.0	231.1	116.5
ROW	249.3	187.6	116.6	135.3	204.6	188.8	162.5	270.3	264.6	216.7	173.9	106.6	352.8	262.5	285.4	246.3	216.8	412.0	260.4	271.4

Table B-4: Adjustments required to the Transaction Cost Matrix for Particleboard, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	185.0	-8.4	-14.8	12.0	15.9	10.1	81.2	141.6	74.3	137.2	125.7	-14.4	277.3	234.8	195.1	254.5	92.9	63.5	155.6	110.3
BC Coast	111.6	39.4	25.0	50.3	34.9	45.6	72.2	131.6	64.1	122.7	68.3	-38.6	266.1	261.0	217.7	282.7	91.3	56.6	145.6	71.1
BC Interior	117.0	36.8	41.7	63.5	45.2	55.8	69.8	129.6	61.9	121.1	67.3	-39.8	264.1	271.1	226.5	288.8	91.4	54.6	143.6	69.8
Alberta	102.9	21.2	22.6	57.7	36.1	46.5	54.8	114.2	46.6	105.0	50.9	-56.3	248.7	261.8	215.8	275.5	74.2	39.2	128.3	51.0
Atlantic Canada	99.5	-1.4	-3.0	28.8	81.4	68.8	83.9	92.8	101.6	86.7	52.8	-0.9	306.6	292.5	220.1	256.2	110.0	88.4	124.6	95.4
Rest of Canada	79.8	-4.6	-6.3	25.4	54.9	68.1	60.8	66.5	85.5	61.5	27.2	-26.5	281.0	282.8	217.6	254.8	84.4	63.1	99.0	67.5
Chile	143.3	14.4	0.2	26.1	62.5	53.2	149.5	148.9	97.9	138.5	102.6	0.7	300.9	282.0	239.1	286.3	149.6	94.4	163.3	108.5
China	81.8	-48.2	-62.0	-36.5	-50.7	-63.1	26.9	125.2	-10.0	107.2	25.9	-56.6	195.1	157.9	123.8	196.7	12.5	-15.4	136.2	41.0
Finland	88.0	-42.3	-56.3	-30.7	31.6	29.4	49.4	63.5	128.6	61.6	34.0	26.2	325.6	247.8	199.6	226.4	81.5	108.2	78.6	91.5
Japan	76.2	-58.2	-71.7	-46.9	-57.9	-69.2	15.4	106.0	-13.0	104.4	22.5	-71.5	185.2	152.9	113.7	177.8	14.0	-25.4	118.0	21.4
New Zealand	180.8	3.4	-9.4	15.0	24.2	12.5	95.5	140.8	75.4	138.5	142.4	-16.4	274.7	239.7	199.5	252.3	95.6	61.1	154.7	112.8
Russian Fed	115.4	-28.8	-41.9	-17.4	45.3	33.5	68.3	133.1	142.3	119.2	58.3	56.6	340.4	264.8	214.6	244.5	101.1	127.0	177.5	95.2
Sweden	93.1	-38.1	-51.9	-26.4	38.8	27.0	54.5	70.8	127.8	62.0	35.5	26.4	332.9	251.0	202.8	230.6	86.5	113.5	82.8	95.2
US North	83.8	-10.0	-11.7	20.0	57.9	62.1	68.9	66.7	83.2	62.9	33.7	-15.9	284.2	288.7	215.7	250.4	89.3	69.0	102.3	79.1
US South	98.1	0.8	-2.3	27.9	39.5	50.8	80.0	86.6	86.9	77.7	47.5	-12.1	290.0	269.6	242.2	271.1	99.5	77.8	111.9	96.9
US West	123.3	31.6	25.9	53.4	41.4	53.9	93.0	125.4	81.6	107.6	66.1	-16.5	283.6	270.2	236.9	309.9	106.5	70.4	151.0	82.7
Rest LA	120.6	-1.0	-12.7	10.9	54.0	42.3	115.1	100.0	95.5	102.6	68.2	-1.0	298.4	268.0	224.2	265.3	158.0	92.7	142.0	118.3
Rest Europe	118.1	-8.8	-22.6	2.9	59.3	47.9	86.8	99.0	149.1	90.1	60.6	51.8	352.3	274.6	229.3	256.2	119.6	152.6	112.1	126.6
Rest Asia	115.2	-14.8	-28.6	-3.0	0.6	-11.1	60.8	155.6	24.6	138.6	59.3	7.3	226.6	212.9	168.5	241.8	73.9	17.1	172.6	74.4
ROW	99.8	-59.3	-72.5	-50.3	1.4	-12.7	35.9	90.4	67.4	71.9	47.3	-45.0	269.0	219.6	183.4	203.4	80.1	61.6	104.4	131.9

Table B-5: Adjustments required to the Transaction Cost Matrix for Fibreboard, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	124.1	83.8	43.7	97.1	92.0	97.7	69.1	207.2	162.7	153.2	113.7	78.5	945.7	-29.7	-50.6	-10.3	59.3	129.6	127.1	-5.5
BC Coast	48.1	129.1	81.0	132.9	108.5	130.7	57.6	194.7	149.9	136.2	53.7	51.7	932.0	-6.1	-30.5	15.5	55.2	120.2	114.6	-47.1
BC Interior	58.9	131.8	103.0	151.5	124.2	146.2	60.6	198.1	153.1	139.9	58.1	55.9	935.4	9.5	-16.3	27.0	60.7	123.6	118.0	-43.1
Alberta	34.1	105.5	73.2	135.0	104.3	126.2	34.8	171.9	127.1	113.1	30.9	28.7	909.3	-10.5	-37.8	2.9	32.7	97.4	91.9	-72.6
Atlantic Canada	14.8	66.8	31.7	90.0	133.7	132.5	48.0	134.5	166.1	78.8	16.9	68.1	951.2	4.2	-49.5	-32.4	52.5	130.6	72.3	-44.2
Rest of Canada	5.2	73.8	38.5	96.7	117.3	141.9	34.9	118.4	160.2	63.8	1.4	52.6	935.7	4.6	-41.9	-23.7	37.1	115.4	56.8	-62.0
Chile	81.3	105.4	57.6	110.1	137.5	139.7	136.3	213.4	185.2	153.5	89.5	92.5	968.2	16.5	-7.7	20.5	114.9	159.4	133.8	-8.3
China	17.3	40.4	-7.0	45.0	21.9	21.0	11.2	187.2	74.8	119.6	10.3	32.8	860.0	-110.2	-125.4	-71.5	-24.6	47.1	104.2	-78.3
Finland	6.3	29.1	-18.6	33.7	86.9	96.3	16.5	108.3	196.2	56.9	1.1	98.3	973.3	-37.5	-66.9	-59.1	27.1	153.5	29.4	-45.1
Japan	2.9	21.5	-25.6	25.8	5.7	5.9	-9.1	159.1	62.9	107.9	-2.0	8.9	841.2	-124.0	-144.4	-99.4	-32.0	28.2	77.1	-106.8
New Zealand	119.4	95.0	48.6	99.7	99.8	99.6	82.9	205.8	163.3	154.0	129.8	75.9	942.7	-25.3	-46.7	-12.9	61.5	126.7	125.8	-3.4
Russian Fed	41.1	49.9	3.2	54.3	108.0	107.7	42.9	185.2	217.3	121.8	32.8	136.1	995.4	-13.0	-44.5	-33.7	54.1	179.7	135.7	-33.9
Sweden	14.2	36.2	-11.3	40.8	96.9	96.7	24.5	118.4	198.2	60.1	5.5	101.4	983.4	-31.4	-60.9	-52.1	35.0	161.7	36.4	-38.5
US North	1.6	60.9	25.6	83.8	112.7	128.4	35.5	111.0	150.2	57.6	0.3	55.7	931.4	2.9	-51.3	-35.6	34.5	113.8	52.6	-57.9
US South	17.9	73.7	36.9	93.7	96.3	119.1	48.6	132.9	156.0	74.4	16.1	61.5	939.1	-14.1	-22.7	-12.9	46.7	124.6	64.2	-38.2
US West	34.8	96.1	56.8	110.9	89.9	113.9	53.3	163.4	142.3	96.0	26.4	48.8	924.4	-21.9	-36.4	17.5	45.3	108.9	94.9	-60.7
Rest LA	59.6	91.1	45.8	96.0	130.1	129.9	103.0	165.6	183.8	118.6	56.1	91.9	966.8	3.5	-21.5	0.5	124.4	158.7	113.5	2.5
Rest Europe	62.5	88.6	41.2	93.3	140.7	140.8	80.0	169.8	242.7	111.4	53.8	150.0	1,026.0	15.4	-11.1	-3.3	91.3	224.0	88.9	16.2
Rest Asia	43.8	66.9	19.4	71.6	66.2	66.0	38.2	210.7	102.5	144.1	36.7	89.7	884.6	-62.1	-87.7	-33.4	29.8	72.7	133.6	-51.8
ROW	62.2	56.1	9.3	58.0	100.7	98.2	47.1	179.3	179.0	111.2	58.5	71.1	960.7	-21.6	-39.0	-38.1	69.8	150.9	99.2	39.4

Table B-6: Adjustments required to the Transaction Cost Matrix for Pulp, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	399.8	152.1	150.2	247.7	301.7	262.8	219.3	202.8	273.8	119.7	143.7	144.8	379.8	122.3	140.6	225.3	181.3	190.8	66.9	183.2
BC Coast	259.6	133.1	123.2	219.2	253.9	231.5	143.5	126.0	196.8	38.5	19.5	53.8	301.8	81.6	96.5	186.7	112.9	117.1	-9.9	77.2
BC Interior	346.0	211.5	220.9	313.3	345.2	322.7	222.1	205.0	275.5	117.8	99.4	133.6	380.8	172.8	186.2	273.8	194.0	196.1	69.1	156.8
Alberta	271.5	135.4	141.3	247.1	275.6	253.0	146.6	129.1	199.8	41.2	22.6	56.7	304.9	103.0	115.0	200.0	116.3	120.2	-6.7	77.6
Atlantic Canada	250.4	95.1	98.1	200.5	303.3	257.6	158.1	90.0	237.1	5.2	6.8	94.4	345.1	116.0	101.6	163.0	134.4	151.6	-28.0	104.3
Rest of Canada	230.7	91.9	94.8	197.1	276.8	256.9	135.0	63.8	221.1	-19.9	-18.8	68.8	319.5	106.3	99.1	161.7	108.8	126.4	-53.6	76.5
Chile	371.1	187.9	178.2	274.7	361.3	318.9	300.6	223.1	310.4	134.0	133.6	173.0	416.4	182.5	197.6	270.1	250.9	234.6	87.7	194.4
China	229.2	44.9	35.6	131.8	167.8	122.3	97.6	119.0	122.1	22.3	-23.5	35.3	230.2	-22.0	1.9	100.2	33.5	44.4	-19.8	46.5
Finland	258.9	74.4	64.9	161.1	273.5	238.3	143.7	80.8	284.2	0.3	8.1	141.5	384.2	91.4	101.2	153.3	126.0	191.5	-53.9	120.5
Japan	202.4	13.7	4.7	100.2	139.3	94.9	64.9	78.6	97.9	-1.7	-48.2	-0.9	199.1	-48.3	-29.4	59.9	13.8	13.2	-59.3	5.7
New Zealand	401.7	169.9	161.7	256.8	316.1	271.3	239.7	208.0	281.0	127.1	166.4	148.9	383.3	133.3	151.1	229.2	190.0	194.4	72.2	191.8
Russian Fed	373.2	174.7	166.1	261.3	374.1	329.2	249.5	237.3	384.8	144.7	119.2	258.9	485.9	195.3	203.1	258.3	232.5	297.3	131.9	211.1
Sweden	239.7	54.2	44.9	141.1	256.4	211.5	124.4	63.7	259.1	-23.7	-14.8	117.4	367.1	70.2	80.1	133.2	106.7	172.6	-74.1	99.9
US North	248.3	100.2	103.0	205.3	293.4	264.4	156.7	77.6	232.3	-5.0	1.3	93.0	336.3	125.8	110.8	170.9	127.4	145.9	-36.7	101.7
US South	309.7	158.0	159.5	260.3	322.0	300.3	214.8	144.6	283.2	56.9	62.2	143.9	389.2	153.9	184.5	238.6	184.7	201.8	20.0	166.5
US West	311.8	165.8	164.6	262.8	300.9	280.3	204.8	160.3	254.8	63.8	57.8	116.5	359.8	131.4	156.1	254.4	168.5	171.4	36.1	129.3
Rest LA	335.7	159.8	152.7	246.9	340.2	295.3	253.5	161.5	295.3	85.5	86.5	158.6	401.2	155.8	170.0	236.4	246.7	220.2	53.7	191.5
Rest Europe	262.2	81.0	71.7	167.9	274.4	230.0	154.2	89.5	277.9	1.9	7.9	140.4	384.1	91.3	104.2	156.3	137.2	209.2	-47.3	128.8
Rest Asia	290.6	106.3	97.1	193.3	247.1	202.3	159.5	177.5	184.7	81.7	37.9	127.2	289.7	61.0	74.7	173.2	122.9	105.0	44.6	108.0
ROW	305.9	92.5	83.8	176.6	278.4	231.3	165.3	142.9	258.1	45.7	56.5	105.5	362.7	98.4	120.2	165.5	159.8	180.1	7.0	196.1

Addendum C – Effective Transaction Costs

Table C-1: Effective Transaction Cost Matrix for Industrial Roundwood, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	-176.5	-192.8	-193.3	-193.7	-196.9	-198.5	-191.3	-188.2	-196.9	-186.7	-179.3	-195.5	-196.4	-197.4	-194.6	-192.3	-194.0	-197.5	-188.2	-190.9
BC Coast	-161.5	-145.2	-147.8	-148.6	-157.0	-154.2	-159.0	-156.1	-164.9	-155.9	-160.0	-167.2	-164.6	-155.6	-153.7	-149.9	-159.6	-164.6	-156.1	-166.7
BC Interior	-132.9	-118.7	-116.1	-117.8	-127.0	-124.2	-132.4	-129.5	-138.3	-129.1	-133.1	-140.4	-138.0	-125.6	-124.1	-121.0	-132.4	-138.0	-129.4	-139.9
Alberta	-149.7	-135.9	-134.3	-132.5	-142.5	-139.8	-149.5	-146.7	-155.5	-146.5	-150.6	-157.9	-155.2	-141.2	-140.1	-137.7	-150.1	-155.2	-146.7	-158.0
Atlantic Canada	-165.0	-156.4	-155.5	-154.6	-144.6	-148.1	-156.0	-166.8	-155.0	-165.8	-164.4	-157.3	-153.9	-147.3	-153.3	-157.3	-154.8	-156.3	-162.0	-160.4
Rest of Canada	-159.6	-146.6	-145.7	-144.9	-141.1	-137.6	-151.6	-163.2	-148.6	-161.9	-160.6	-153.5	-150.1	-139.2	-143.2	-146.9	-151.0	-152.4	-158.2	-157.2
Chile	-214.6	-213.6	-216.1	-216.8	-211.1	-213.7	-193.5	-213.1	-217.4	-213.2	-212.4	-218.2	-216.9	-211.5	-209.5	-210.5	-205.5	-216.1	-213.0	-218.2
China	-210.8	-210.0	-212.4	-213.2	-221.2	-224.7	-212.4	-199.0	-226.1	-201.2	-212.7	-213.3	-225.0	-224.6	-220.2	-214.3	-222.1	-225.3	-199.8	-216.0
Finland	-311.7	-311.1	-313.5	-314.3	-301.7	-302.3	-309.0	-318.4	-291.3	-316.2	-313.1	-293.6	-292.4	-303.0	-302.4	-308.9	-306.1	-294.5	-318.0	-305.0
Japan	-220.4	-220.9	-223.2	-224.2	-231.4	-234.5	-223.6	-212.4	-235.0	-210.2	-221.7	-225.5	-235.8	-234.1	-231.1	-227.6	-229.8	-236.1	-212.9	-229.5
New Zealand	-180.4	-192.5	-194.7	-195.7	-197.4	-200.7	-190.3	-191.3	-199.4	-189.2	-177.6	-198.8	-199.9	-198.9	-196.2	-195.7	-196.1	-201.0	-191.3	-193.0
Russian Fed	-214.7	-217.8	-220.0	-221.1	-208.4	-211.6	-214.2	-209.9	-198.0	-211.0	-216.9	-173.5	-198.8	-208.7	-208.7	-214.4	-211.2	-199.8	-201.7	-214.4
Sweden	-236.7	-236.3	-238.7	-239.5	-226.1	-229.4	-234.0	-242.8	-217.9	-242.5	-239.1	-219.9	-216.8	-228.5	-228.0	-234.2	-231.1	-219.5	-243.3	-230.4
US North	-309.8	-299.3	-298.5	-297.6	-291.6	-290.5	-300.7	-314.5	-300.6	-312.8	-310.2	-301.9	-300.6	-288.9	-295.1	-299.4	-301.0	-302.1	-308.6	-305.3
US South	-275.8	-266.2	-265.7	-265.3	-266.3	-263.3	-267.5	-278.9	-269.3	-278.6	-276.2	-270.7	-268.8	-263.8	-257.7	-263.6	-268.0	-269.5	-275.8	-270.3
US West	-315.5	-304.5	-304.7	-305.0	-312.4	-309.1	-310.6	-315.0	-317.4	-317.1	-317.8	-318.4	-317.1	-310.3	-305.7	-299.7	-312.7	-318.1	-311.8	-320.8
Rest LA	-165.1	-162.1	-163.9	-165.2	-157.8	-161.0	-153.4	-170.7	-162.4	-167.3	-166.1	-163.1	-161.9	-159.7	-157.9	-160.6	-147.6	-160.9	-163.1	-160.0
Rest Europe	-189.4	-187.8	-190.3	-191.1	-180.0	-183.2	-184.7	-194.6	-171.6	-194.3	-191.8	-172.5	-171.0	-181.6	-180.2	-186.7	-181.7	-168.4	-194.8	-181.4
Rest Asia	-294.1	-293.4	-295.8	-296.6	-299.8	-303.0	-295.6	-283.2	-309.1	-285.1	-296.0	-288.4	-308.9	-302.1	-300.5	-294.5	-297.9	-308.9	-282.4	-299.4
ROW	-141.4	-148.5	-150.8	-152.5	-142.7	-146.6	-145.5	-144.0	-140.7	-146.3	-142.4	-145.7	-140.6	-143.4	-139.7	-148.0	-139.4	-140.0	-144.0	-127.0

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	-6.8	-25.9	-51.8	-50.9	-34.4	-25.0	-55.0	-3.3	13.7	-17.4	-48.5	-59.3	11.1	51.0	31.0	41.0	-24.0	-55.9	2.0	-20.3
BC Coast	53.6	44.4	18.5	19.4	35.8	45.3	16.8	67.0	84.2	53.3	22.8	12.9	81.6	91.6	71.6	81.6	46.2	14.4	72.3	50.0
BC Interior	78.7	68.2	42.4	43.3	59.7	69.2	42.8	90.9	108.3	77.7	48.0	39.3	105.7	119.3	99.3	109.3	70.1	38.3	96.2	73.9
Alberta	72.6	62.1	36.3	37.2	53.6	63.1	36.6	84.8	102.2	71.6	41.8	33.2	99.6	100.1	80.1	90.1	64.0	32.2	90.1	67.8
Atlantic Canada	51.6	41.9	16.1	17.0	33.4	42.9	15.1	64.6	81.8	51.0	20.8	11.3	79.2	118.8	98.8	108.8	43.8	11.9	69.8	47.6
Rest of Canada	56.9	47.7	21.9	22.8	39.2	48.7	20.1	70.4	87.5	56.7	26.1	16.2	85.0	114.7	94.7	104.7	49.6	17.8	75.7	53.4
Chile	36.4	26.6	0.8	1.6	18.1	27.6	14.9	49.3	66.5	35.8	5.6	-3.7	63.9	103.5	83.5	93.5	28.5	-3.4	54.5	17.4
China	0.7	-7.4	-33.2	-32.3	-15.9	-6.4	-36.7	15.3	32.2	1.1	-30.1	-41.1	29.6	69.5	49.5	59.5	-5.5	-37.4	20.5	-1.7
Finland	46.1	39.0	13.1	14.0	30.5	39.9	8.1	61.7	80.8	47.1	15.3	3.3	75.8	115.9	95.9	105.9	40.9	9.0	66.9	44.7
Japan	8.7	0.2	-25.7	-24.8	-8.3	1.1	-28.4	22.9	39.9	13.1	-22.0	-32.6	37.3	77.1	57.1	67.1	2.1	-29.8	28.1	5.9
New Zealand	23.9	14.1	-11.8	-10.9	5.5	15.0	-12.5	36.7	54.0	23.3	2.4	-16.2	51.4	91.0	71.0	81.0	15.9	-15.9	42.0	19.7
Russian Fed	36.3	26.5	0.7	1.5	18.0	27.4	-0.1	49.2	66.4	35.7	5.5	14.8	63.8	103.4	83.4	93.4	28.4	-3.5	54.4	-14.4
Sweden	92.5	85.2	59.4	60.3	76.7	86.2	54.6	107.9	124.6	93.4	61.7	49.8	124.4	162.1	142.1	152.1	87.1	55.2	113.1	90.9
US North	-35.2	-40.5	-66.4	-65.5	-49.1	-39.6	-74.2	-17.9	-1.5	-33.1	-66.0	-79.7	-4.1	36.4	16.4	26.4	-38.7	-70.5	-12.6	-34.9
US South	-23.9	-30.2	-56.1	-55.2	-38.8	-29.3	-62.3	-7.6	9.0	-22.4	-54.7	-67.4	6.4	46.7	26.7	36.7	-28.4	-60.2	-2.3	-24.6
US West	-45.0	-50.9	-76.7	-75.8	-59.4	-49.9	-83.8	-28.2	-11.7	-43.3	-75.8	-89.1	-14.3	26.0	6.0	16.0	-49.0	-80.9	-23.0	-45.2
Rest LA	59.5	50.4	24.6	25.4	41.9	51.3	22.7	73.1	90.2	59.3	28.7	18.7	87.6	127.3	107.3	117.3	52.3	20.4	78.3	56.1
Rest Europe	22.7	12.0	-13.9	-13.0	3.5	12.9	-13.1	34.6	52.1	21.5	-8.1	-16.5	49.5	88.9	68.9	78.9	13.9	-18.0	39.9	17.6
Rest Asia	-4.1	-11.9	-37.8	-36.9	-20.5	-11.0	-41.7	10.7	27.6	-3.6	-34.9	-46.2	25.0	65.0	45.0	55.0	-10.1	-41.9	16.0	-6.3
ROW	73.6	64.6	38.8	39.7	56.1	65.6	36.7	87.3	104.4	73.5	42.8	32.6	101.8	141.5	121.5	131.5	66.5	34.7	92.6	70.3

Table C-3: Effective Transaction Cost Matrix for Plywood + Veneer, Twenty Model Regions, $(\$/\mathrm{m}^3)$

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	237.5	202.3	139.6	164.7	197.8	196.2	165.9	268.0	250.3	223.1	165.9	110.6	337.9	258.3	267.2	259.1	197.4	395.0	258.1	206.3
BC Coast	207.2	171.9	109.2	134.3	167.4	165.9	135.6	237.6	220.0	192.8	135.6	80.3	307.6	228.0	236.9	228.7	167.1	364.6	227.7	175.9
BC Interior	233.1	197.8	135.1	160.2	193.3	191.8	161.5	263.6	245.9	218.7	161.5	106.2	333.5	253.9	262.8	254.7	193.0	390.6	253.6	201.8
Alberta	225.9	190.6	127.9	153.0	186.1	184.6	154.2	256.3	238.6	211.5	154.2	99.0	326.3	246.7	255.5	247.4	185.8	383.3	246.4	194.6
Atlantic Canada	201.2	165.9	103.2	128.3	161.4	159.8	129.5	231.6	213.9	186.7	129.5	74.2	301.6	222.0	230.8	222.7	161.1	358.6	221.7	169.9
Rest of Canada	204.6	169.3	106.6	131.7	164.8	163.2	132.9	235.0	217.3	190.1	132.9	77.6	304.9	225.3	234.2	226.1	164.4	362.0	225.1	173.3
Chile	235.4	200.2	137.5	162.6	195.7	194.1	163.8	265.9	248.2	221.0	163.8	108.5	335.8	256.2	265.1	257.0	195.3	392.9	256.0	204.2
China	222.6	187.3	124.6	149.7	182.8	181.2	150.9	253.0	235.3	208.1	150.9	95.6	323.0	243.3	252.2	244.1	182.4	380.0	243.1	191.3
Finland	176.6	141.3	78.6	103.7	136.8	135.2	104.9	207.0	189.3	162.1	104.9	49.6	277.0	197.4	206.2	198.1	136.5	334.0	197.1	145.3
Japan	195.8	160.5	97.8	122.9	156.0	154.5	124.1	226.2	208.5	181.3	124.1	68.9	296.2	216.6	225.4	217.3	155.7	353.2	216.3	164.5
New Zealand	236.6	201.3	138.6	163.7	196.8	195.2	164.9	267.0	249.3	222.1	164.9	109.6	337.0	257.3	266.2	258.1	196.4	394.0	257.1	205.3
Russian Fed	205.1	169.8	107.1	132.2	165.3	163.8	133.4	235.5	217.8	190.7	133.4	78.2	305.5	225.9	234.7	226.6	165.0	362.5	225.6	173.8
Sweden	193.9	158.6	95.9	121.0	154.1	152.6	122.3	224.4	206.7	179.5	122.3	67.0	294.3	214.7	223.6	215.5	153.8	351.4	214.4	162.6
US North	155.0	119.7	57.0	82.1	115.2	113.6	83.3	185.4	167.7	140.5	83.3	28.0	255.3	175.7	184.6	176.5	114.8	312.4	175.5	123.7
US South	170.2	135.0	72.3	97.4	130.5	128.9	98.6	200.7	183.0	155.8	98.6	43.3	270.6	191.0	199.9	191.8	130.1	327.7	190.8	139.0
US West	139.4	104.1	41.4	66.5	99.7	98.1	67.8	169.9	152.2	125.0	67.8	12.5	239.8	160.2	169.1	161.0	99.3	296.9	159.9	108.1
Rest LA	237.5	202.2	139.5	164.6	197.7	196.2	165.8	267.9	250.2	223.1	165.8	110.6	337.9	258.3	267.1	259.0	197.4	394.9	258.0	206.2
Rest Europe	253.8	218.5	155.8	180.9	214.0	212.4	182.1	284.2	266.5	239.3	182.1	126.8	354.2	274.6	283.4	275.3	213.7	411.2	274.3	222.5
Rest Asia	210.6	175.3	112.6	137.7	170.8	169.2	138.9	241.0	223.3	196.1	138.9	83.6	311.0	231.4	240.2	232.1	170.5	368.0	231.1	179.3
ROW	302.7	267.4	204.7	229.8	262.9	261.3	231.0	333.1	315.4	288.2	231.0	175.7	403.1	323.5	332.3	324.2	262.6	460.1	323.2	271.4

Table C-4: Effective Transaction Cost Matrix for Particleboard, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	185.0	52.2	47.4	75.9	91.4	91.7	136.2	185.0	150.0	175.2	136.2	55.9	351.0	312.3	262.1	313.0	157.7	141.5	199.0	163.7
BC Coast	172.2	39.4	34.6	63.1	78.6	78.9	123.4	172.2	137.2	162.4	123.4	43.1	338.2	299.5	249.3	300.2	144.9	128.7	186.2	150.9
BC Interior	179.2	46.5	41.7	70.2	85.6	85.9	130.4	179.3	144.2	169.4	130.4	50.2	345.3	306.6	256.3	307.2	151.9	135.8	193.2	157.9
Alberta	166.8	34.0	29.2	57.7	73.2	73.5	118.0	166.8	131.8	157.0	118.0	37.7	332.8	294.1	243.9	294.8	139.5	123.3	180.8	145.5
Atlantic Canada	175.0	42.3	37.4	65.9	81.4	81.7	126.2	175.0	140.0	165.2	126.2	45.9	341.0	302.4	252.1	303.0	147.7	131.5	189.0	153.7
Rest of Canada	161.4	28.6	23.8	52.3	67.8	68.1	112.6	161.4	126.4	151.6	112.6	32.3	327.4	288.7	238.5	289.4	134.1	117.9	175.4	140.1
Chile	198.4	65.6	60.8	89.3	104.7	105.0	149.5	198.4	163.3	188.5	149.5	69.3	364.4	325.7	275.5	326.4	171.0	154.9	212.3	177.0
China	125.2	-7.6	-12.4	16.1	31.6	31.8	76.4	125.2	90.2	115.4	76.4	-3.9	291.2	252.5	202.3	253.2	97.9	81.7	139.2	103.9
Finland	163.6	30.9	26.1	54.5	70.0	70.3	114.8	163.7	128.6	153.8	114.8	34.6	329.7	291.0	240.7	291.6	136.3	120.2	177.6	142.3
Japan	114.2	-18.6	-23.4	5.1	20.6	20.9	65.4	114.2	79.2	104.4	65.4	-14.9	280.2	241.5	191.3	242.2	86.9	70.7	128.2	92.9
New Zealand	191.2	58.5	53.7	82.1	97.6	97.9	142.4	191.3	156.2	181.4	142.4	62.2	357.3	318.6	268.3	319.2	163.9	147.8	205.2	169.9
Russian Fed	185.7	52.9	48.1	76.6	92.1	92.3	136.9	185.7	150.7	175.9	136.9	56.6	351.7	313.0	262.8	313.7	158.4	142.2	199.7	164.4
Sweden	166.8	34.1	29.3	57.7	73.2	73.5	118.0	166.9	131.8	157.0	118.0	37.8	332.9	294.2	243.9	294.8	139.5	123.4	180.8	145.5
US North	161.4	28.6	23.8	52.3	67.8	68.0	112.6	161.4	126.4	151.5	112.6	32.3	327.4	288.7	238.5	289.4	134.0	117.9	175.4	140.1
US South	165.1	32.4	27.6	56.1	71.5	71.8	116.3	165.2	130.1	155.3	116.3	36.1	331.2	292.5	242.2	293.1	137.8	121.7	179.1	143.8
US West	181.9	49.1	44.3	72.8	88.2	88.5	133.0	181.9	146.8	172.0	133.0	52.8	347.9	309.2	259.0	309.9	154.5	138.4	195.8	160.5
Rest LA	185.4	52.6	47.8	76.3	91.7	92.0	136.5	185.4	150.3	175.5	136.5	56.3	351.4	312.7	262.5	313.4	158.0	141.9	199.3	164.0
Rest Europe	196.1	63.3	58.5	87.0	102.5	102.8	147.3	196.1	161.1	186.3	147.3	67.0	362.1	323.4	273.2	324.1	168.8	152.6	210.1	174.8
Rest Asia	158.6	25.8	21.0	49.5	65.0	65.2	109.8	158.6	123.6	148.7	109.8	29.5	324.6	285.9	235.7	286.6	131.2	115.1	172.6	137.3
ROW	153.2	20.5	15.7	44.2	59.6	59.9	104.4	153.3	118.2	143.4	104.4	24.2	319.3	280.6	230.4	281.2	125.9	109.8	167.2	131.9

Table C-5: Effective Transaction Cost Matrix for Fibreboard, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	124.1	144.4	106.0	161.0	167.5	179.3	124.1	250.6	238.4	191.2	124.1	148.8	1,019.5	47.9	16.4	48.3	124.1	207.6	170.5	47.9
BC Coast	108.8	129.1	90.6	145.7	152.2	163.9	108.8	235.3	223.0	175.9	108.8	133.5	1,004.1	32.5	1.1	33.0	108.8	192.3	155.2	32.6
BC Interior	121.2	141.5	103.0	158.1	164.6	176.3	121.2	247.7	235.4	188.3	121.2	145.9	1,016.6	44.9	13.5	45.4	121.2	204.7	167.6	45.0
Alberta	98.0	118.3	79.9	135.0	141.4	153.2	98.0	224.5	212.3	165.1	98.0	122.7	993.4	21.8	-9.6	22.2	98.0	181.5	144.5	21.9
Atlantic Canada	90.3	110.5	72.1	127.2	133.7	145.4	90.3	216.8	204.5	157.3	90.3	115.0	985.6	14.0	-17.4	14.4	90.3	173.8	136.7	14.1
Rest of Canada	86.8	107.1	68.6	123.7	130.2	141.9	86.8	213.3	201.0	153.8	86.8	111.5	982.1	10.5	-20.9	10.9	86.8	170.3	133.2	10.6
Chile	136.3	156.6	118.2	173.3	179.8	191.5	136.3	262.9	250.6	203.4	136.3	161.0	1,031.7	60.1	28.7	60.5	136.3	219.9	182.8	60.2
China	60.7	81.0	42.6	97.7	104.1	115.9	60.7	187.2	175.0	127.8	60.7	85.4	956.1	-15.5	-46.9	-15.1	60.7	144.2	107.2	-15.4
Finland	81.9	102.2	63.8	118.9	125.3	137.1	81.9	208.4	196.2	149.0	81.9	106.6	977.3	5.7	-25.7	6.1	81.9	165.4	128.4	5.8
Japan	40.8	61.1	22.7	77.8	84.2	96.0	40.8	167.3	155.1	107.9	40.8	65.5	936.2	-35.4	-66.8	-35.0	40.8	124.3	87.3	-35.3
New Zealand	129.8	150.1	111.7	166.8	173.2	185.0	129.8	256.3	244.1	196.9	129.8	154.5	1,025.2	53.6	22.2	54.0	129.8	213.3	176.3	53.7
Russian Fed	111.4	131.7	93.2	148.3	154.8	166.5	111.4	237.9	225.6	178.5	111.4	136.1	1,006.8	35.1	3.7	35.6	111.4	194.9	157.8	35.2
Sweden	88.0	108.3	69.8	124.9	131.4	143.2	88.0	214.5	202.2	155.1	88.0	112.7	983.4	11.8	-19.7	12.2	88.0	171.5	134.4	11.8
US North	79.2	99.5	61.0	116.1	122.6	134.3	79.2	205.7	193.4	146.2	79.2	103.9	974.5	2.9	-28.5	3.3	79.2	162.7	125.6	3.0
US South	84.9	105.2	66.8	121.9	128.4	140.1	84.9	211.5	199.2	152.0	84.9	109.6	980.3	8.7	-22.7	9.1	84.9	168.5	131.4	8.8
US West	93.3	113.6	75.2	130.3	136.7	148.5	93.3	219.8	207.6	160.4	93.3	118.0	988.7	17.1	-14.3	17.5	93.3	176.8	139.8	17.2
Rest LA	124.4	144.7	106.3	161.3	167.8	179.6	124.4	250.9	238.7	191.5	124.4	149.1	1,019.8	48.2	16.7	48.6	124.4	207.9	170.8	48.2
Rest Europe	140.5	160.8	122.3	177.4	183.9	195.6	140.5	267.0	254.7	207.6	140.5	165.2	1,035.8	64.2	32.8	64.7	140.5	224.0	186.9	64.3
Rest Asia	87.2	107.5	69.0	124.1	130.6	142.4	87.2	213.7	201.5	154.3	87.2	111.9	982.6	11.0	-20.5	11.4	87.2	170.7	133.6	11.0
ROW	115.6	135.9	97.5	152.5	159.0	170.8	115.6	242.1	229.9	182.7	115.6	140.3	1,011.0	39.4	7.9	39.8	115.6	199.1	162.0	39.4

Table C-6: Effective Transaction Cost Matrix for Pulp, Twenty Model Regions, ($/m^3)

Export/Import	Australia	BC Coast	BC Interior	Alberta	Atlantic Canada	Rest of Canada	Chile	China	Finland	Japan	New Zealand	Russian Fed	Sweden	US North	US South	US West	Rest LA	Rest Europe	Rest Asia	ROW
Australia	399.8	212.7	212.5	311.6	377.2	344.4	274.3	246.2	349.5	157.7	154.1	215.2	453.5	199.8	207.7	283.8	246.1	268.8	110.4	236.6
BC Coast	320.2	133.1	132.9	232.0	297.6	264.8	194.7	166.6	269.9	78.1	74.5	135.6	373.9	120.2	128.1	204.2	166.5	189.2	30.8	157.0
BC Interior	408.2	221.1	220.9	320.0	385.6	352.8	282.7	254.6	357.9	166.1	162.5	223.6	461.9	208.2	216.0	292.2	254.5	277.2	118.7	245.0
Alberta	335.4	148.3	148.0	247.1	312.8	279.9	209.8	181.8	285.0	93.2	89.7	150.7	389.0	135.3	143.2	219.4	181.6	204.3	45.9	172.1
Atlantic Canada	325.9	138.8	138.5	237.6	303.3	270.4	200.3	172.3	275.5	83.7	80.2	141.2	379.5	125.9	133.7	209.9	172.1	194.8	36.4	162.6
Rest of Canada	312.3	125.2	124.9	224.1	289.7	256.9	186.8	158.7	261.9	70.1	66.6	127.6	366.0	112.3	120.1	196.3	158.5	181.2	22.8	149.0
Chile	426.2	239.1	238.8	337.9	403.6	370.7	300.6	272.6	375.8	184.0	180.5	241.5	479.8	226.2	234.0	310.2	272.4	295.1	136.7	262.9
China	272.6	85.5	85.3	184.4	250.0	217.2	147.1	119.0	222.3	30.5	26.9	88.0	326.3	72.6	80.4	156.6	118.9	141.6	-16.8	109.4
Finland	334.6	147.5	147.2	246.3	312.0	279.1	209.1	181.0	284.2	92.4	88.9	149.9	388.2	134.6	142.4	218.6	180.8	203.5	45.1	171.3
Japan	240.4	53.3	53.0	152.2	217.8	185.0	114.9	86.8	190.1	-1.7	-5.3	55.7	294.1	40.4	48.2	124.4	86.6	109.3	-49.1	77.1
New Zealand	412.1	225.0	224.7	323.9	389.5	356.7	286.6	258.5	361.8	170.0	166.4	227.5	465.8	212.1	219.9	296.1	258.4	281.1	122.6	248.9
Russian Fed	443.5	256.4	256.1	355.3	420.9	388.1	318.0	289.9	393.2	201.4	197.8	258.9	497.2	243.5	251.3	327.5	289.8	312.5	154.0	280.3
Sweden	313.4	126.3	126.0	225.2	290.8	258.0	187.9	159.8	263.1	71.3	67.7	128.8	367.1	113.4	121.2	197.4	159.7	182.4	23.9	150.2
US North	325.8	138.8	138.5	237.6	303.2	270.4	200.3	172.2	275.5	83.7	80.1	141.2	379.5	125.8	133.7	209.8	172.1	194.8	36.4	162.6
US South	376.7	189.6	189.3	288.5	354.1	321.3	251.2	223.1	326.3	134.5	131.0	192.0	430.4	176.7	184.5	260.7	222.9	245.6	87.2	213.4
US West	370.4	183.3	183.0	282.1	347.8	314.9	244.9	216.8	320.0	128.2	124.7	185.7	424.0	170.4	178.2	254.4	216.6	239.3	80.9	207.1
Rest LA	400.5	213.4	213.1	312.3	377.9	345.1	275.0	246.9	350.1	158.3	154.8	215.8	454.2	200.5	208.3	284.5	246.7	269.4	111.0	237.2
Rest Europe	340.2	153.1	152.8	252.0	317.6	284.8	214.7	186.6	289.9	98.1	94.5	155.6	393.9	140.2	148.0	224.2	186.5	209.2	50.7	177.0
Rest Asia	334.1	147.0	146.7	245.8	311.4	278.6	208.5	180.5	283.7	91.9	88.4	149.4	387.7	134.0	141.9	218.0	180.3	203.0	44.6	170.8
ROW	359.3	172.2	172.0	271.1	336.7	303.9	233.8	205.7	309.0	117.2	113.6	174.7	413.0	159.3	167.1	243.3	205.6	228.3	69.8	196.1