Productivity and Technology Adoption in the Alberta Forest Sector

by

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Abstract

The competitiveness of the Canadian forest sector is facing threats from multiple directions including supply constraints due to the Mountain Pine Beetle devastation and unusually high fire losses. Consequently, the need to improve productivity of the forest sector is paramount to maintaining global competitiveness. The adoption of genomic technology and the use of improved seeds are expected to improve timber productivity in the near future. However, this improvement will need to take place within the confines of the public-private nature of the sector where 93% of the total forest area is publicly owned.

Stringent government regulations can hinder competitiveness by imposing a cost on production. To gain some insights into the extent to which stringent forest regulatory policies have slowed down technical change and negatively affected productivity in the forest sector, I investigate the production structure of the Alberta logging industry. Specifically, I examine the nature of factor substitution, and estimate the rate of technical change and total factor productivity growth. A key finding is that both the rate of technical change and total factor productivity growth are negative in most years in my sample. I also find low elasticities of substitution between inputs and that technical change has been material-neutral.

Government policy can also reduce the incentives for firms to adopt new technologies by increasing uncertainties and limiting the benefit of new technologies. To explore the extent to which government policies can affect the welfare outcomes of adopting a productivity-enhancing technology, I calculate the economic returns to the adoption of genomics-assisted tree breeding (GATB) in Alberta under different breeding and policy scenarios. I find that the payoffs of GATB research are large. However, the results also demonstrate that when the level of genetic gain approved by the government is low, the economic returns can be negative and therefore discourage the adoption of genomic technology.

This study provide some evidence that Alberta's regulations have reduced incentives for forest companies to improve its overall productivity. These findings have important policy and investment implications to the government and forest companies in Alberta.

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Acronyms

AAC annual allowable cut

ACE allowable cut effect

AES Allen elasticities of substitution

BAU business as usual

GATB genomics-assisted tree breeding

IS improved seed

MES Morishima elasticities of substitution

MPB Mountain Pine Beetle

RES-FOR Resilient Forests

ROC rest of Canada

RTC rate of technical change

SWL softwood lumber

TB traditional breeding

TFP total factor productivity

Chapter 1: Introduction

1.1 Overview of Canada's Forest Sector

Canada has 9% of the world's forests which contain approximately 47 billion cubic meters of wood (Natural Resources Canada, 2017). Canada is committed to sustainable forest management which is a way of using and caring for forests to maintain their environmental, social and economic values and benefits over time (Natural Resources Canada, 2016). The extensive forest base is the foundation of Canada's forest industry, which consist of upstream activities (e.g., forestry management and logging), traditional forest products (e.g., pulp and paper and solid wood products), and non-traditional forest products (e.g., advanced bioproducts). In 2016, the forest industry contributed over $23.1 billion (1.2%) to Canada's nominal gross domestic product (GDP) and accounted for about 7% of Canada's total exports (Natural Resources Canada, 2017).

While forestry continues to be one of Canada's economic engines, Canada's forest sector has been struggling for competitiveness in recent years, reflected by almost a 20% decrease of its contribution to real GDP from 2005 to 2016 due to a combination of market and environmental factors. Key challenges continue to revolve around environmental threats (e.g., destruction caused by fires and insect outbreaks (McKenney et al., 2016)), economic threats (e.g., emerging low cost competitors (Anderson et al., 2015)), technological threats (e.g., the move toward the use of engineered products instead of traditional solid wood products (McKeever, 1997)), and regulatory threats (e.g., changes to environmental quality regulations (Bernstein and Cashore, 2001)). A complication in addressing these challenges is the Canadian tenure system: 94% of the forest lands is publicly owned but harvested by private forest companies. Industry requires more incentives to invest in research and development (R&D), especially given the long production growth cycle on primarily Crown lands: up to 120 years in northern boreal forests.

The need to improve productivity is paramount to maintaining global competitiveness. One obvious strategy is to inspire technical change and promote the use of cutting-edge technologies. In fact, the potential for enhancing forest productivity and diversifying forest fibre based products and markets have offered a number of opportunities for genomics applications (Genome BC, 2017). Over the past several years, knowledge of, and interest in, genomics have increased dramatically among researchers, policy makers and key end-users. Approximately 150 C$ million has been invested in advancing forest genomics R&D across the country from 2000 to 2016 (Genome Canada, 2017). These investments relates to improving the productivity of current and future forests and protecting the health of Canada's forests (Genome Canada, 2017). Advances in genomics R&D provide new tools to manage the resource, assure the long-term security of the timber source, and maintain Canada's position as having the largest sustainably managed forest resource across the globe (Genome Canada, 2013).

1.2 Using Genomics to Increase the Productivity of the Forest Sector

Genomics-assisted tree breeding (GATB) describes the tree improvement process that uses genomic selection instead of traditional pedigree selection to advance improvement in growth and yield from one generation to the next. Genomics is a biotechnology that focuses on the DNA sequence of the entire organism's genome (Porth et al., 2015). Prior to the availability of DNA sequence information, the testing phases of tree improvement relied entirely on pedigree selection combined with progeny performance information (phenotypic data) in order to estimate breeding values for the parents in the tree improvement program. This progeny testing process can take up to 20 years, making the traditional breeding (TB) process time- and resource-demanding. With genomic selection, the second breeding cycle can be significantly shortened once the prediction models are developed for genomic selection because there is no requirement for the progeny testing process. Moreover, genomic selection delivers more accurate breeding values and allows for a higher intensity of selection (Porth et al., 2015; Ratcliffe et al., 2017). Genomic selection generally can be summarized into two steps. According to Grattapaglia (2017), the first step is to develop prediction models by establishing the linkage between a DNA chromosome segment and the relevant phenotypic traits in a reference or training population. This step requires both phenotypic and genotypic information. The second step is to apply the prediction models to "selection candidates" or verification population for which only genotypic information are collected (Grattapaglia, 2017).

Forest companies can increase their harvesting and wood product production by increasing the productivity of forest lands through tree improvement. In many Canadian provinces, though the final harvest levels of each forest company are constrained by the government through an annual allowable cut (AAC), forest companies can increase their AAC through an allowable cut effect (ACE) (Luckert and Haley, 1995). An ACE is an immediate increase in today's allowable cut which is attributable to the expected future increases in timber yield (Schweitzer et al., 1972). If a tree improvement program can produce improved seed (IS) that has higher genetic volume gain (i.e., higher yield) and the forest company use the IS for reforestation, the government can approve an ACE for the company immediately given the fact that the reforested lands will have a higher yield in the future.

An ACE that is attributable to the tree improvement program cannot be realized until the breeding and selection process is finished and sufficient IS are produced in the corresponding seed orchard. This indicates that if the R&D lag of GATB is shorter than TB, an ACE (i.e., timber supply increase) can be realized earlier when GATB is adopted. Therefore, economic returns can be realized sooner with application of GATB research. Additionally, the shorter breeding cycle nature of GATB allows forest companies to respond faster to changes in the economic objectives of the forest products, market demands, and management policies, which can help the companies increase their productivity outcomes. With the genomics information available for parents in the seed orchard, new traits of interest can be rapidly assessed and selected for using GATB.

1.3 Economic Research Problem

Productivity performance matters because it is a key driver of long-term economic growth and prosperity. Individual consumer benefits from improved productivity as lower product costs can translate into lower consumer prices and improved product availability; society as a whole also benefits because fewer scarce resources are required to produce the same quantity of goods and services. Productivity is influenced by government regulations. Nicoletti and Scarpetta (2003) describe two main areas of regulation that are likely to have an impact on product market competition and cost of production: (1) regulations that aim at establishing partial or full state control over resources or economic activities (e.g., public ownership and/or control, restrictions on price setting); (2) and regulations that create barriers to entrepreneurship in domestic markets. These barriers include regulations limiting the number of competitors; structural arrangements that make it difficult for competitors to access fixed networks (e.g., vertical integration); regulatory and administrative burdens that impose fixed costs on businesses; and policies that create impediments to international trade and investment (e.g., foreign investment restrictions).

Using these two areas of regulation as criterions, the Canadian forest industry is highly regulated. For example, in the province of Alberta, the government owns all timber located on provincial public land, while the right to harvest timber on public land is mainly allocated to companies and individuals through an area- or volume-based tenure system (Alberta Agriculture and Forestry, 2018). These private forest companies operate and are responsible for the management of the forest within their respective forest management areas, which includes planning, silvicultural treatments, reforestation and conservation requirements (Luckert et al., 2011). Alberta has the most stringent nominal rules limiting clear-cut size; the mill appurtenancy rule in Alberta requires tenure holders to own and operate wood processing facilities, which can be seen as a barrier of entry; and Alberta restricts foreign direct investment in timberland (Anderson et al., 2015).

Regulation by government usually imposes a cost on producers and therefore may result in reduced productivity and reduced ability to compete with firms in other regions without such regulations. Neoclassical microeconomics assumes that all firms pursue a goal of profit maximization. When a firm is producing at the profit maximizing output level or is forced to produce at some other output level, it seeks the combination of inputs that minimizes the cost of producing that output level. To minimize the cost, firms will adjust their supplies, the technology they adopt for production, management structure, geographic location, the mix of inputs they use in production, and any other factor that will reduce costs of production. Since regulations force producers to behave in ways that they would not act voluntarily, it is reasonable to expect that regulations increase production costs and prevent firms from maximizing productivity. Previous studies have argued that inflexible and rather static tenure systems currently in place in Canada is likely to discourage productivity improvement and lead to a gradual weakening of the forest sector in the global marketplace (Haley and Nelson, 2007; Kant, 2009; Vertinsky and Luckert, 2010).

Regulations limiting competition pressure, such as creating fixed costs to affect the ability of firms to enter markets, can hinder the productivity improvements via the incentives to technical change. Researchers suggest that intensified competition may force firms to increase the rate of technical change and R&D investment in order to acquire a lead over their competitors (Aghion et al., 1998). Based on an empirical study among Organization for Economic Co-operation and Development (OECD) countries, Nicoletti and Scarpetta (2003) find that policy reforms promoting competition tend to inspire innovation and boost productivity.

Some regulatory policies can reduce the incentives to adopt new technologies by increasing uncertainties and limiting the benefits of new technologies. For example, if the use of a new technology is partially or completely restricted by government regulations, the benefits of the technology can never be realized and the technology is less likely to be adopted.

Given the challenges facing the forest sector and the fact that the forest industry is highly-regulated in Canada, the economic problem that I address in this study is the effect of government intervention on productivity and technology adoption in the forest sector. Specifically, I first look at the government policy arrangements and productivity performance which provide clues as to the ways in which regulation may have a bearing for productivity outcomes. I then explore the extent to which government policies can affect the welfare outcomes of adopting a productivity-enhancing technology (i.e., genomic technology).

1.4 Study Motivation and Objectives

The empirical setting of this study is the forest industry of Alberta, Canada. The Alberta forest sector shares the same challenges described in section 1.1. Additionally, the combined effects of land use shifts, along with the effects of a changing climate (e.g., increased pest and fire losses), will see an ongoing pressure on commercially and economically available timber supply in the near future (Schreiber and Thomas, 2017). According to McDermott et al. (2010), Alberta is subject to some of the most stringent forest management regulations in North America as forest policies in Alberta are substantive and mostly non-discretionary. Therefore, I use the Alberta forest industry as a case study to illustrate the potential impacts of government regulations on productivity and technology adoption.

This research has two main objectives. The first objective is to gain some insights into the extent to which stringent forest regulatory policies in Alberta have slowed down technical change and negatively affected productivity in the forest sector by investigating the production structure of the Alberta logging industry. I then articulate options based on the empirical results to help the Alberta government and private forest companies respond to current and future challenges facing the forest sector. The second objective is to assess the returns to R&D from GATB under different policy scenarios. The findings of this objective reveal the conditions under which the adoption of genomic technology is beneficial, and therefore can be useful in guiding investment decisions on genomic technology and policy decisions on the use of the ACE policy instrument in Alberta.

The contributions of this research go beyond its role as a case study of estimating productivity growth and returns to forestry genomics R&D in Alberta. Though forest management policies vary considerably across provinces in Canada, the general features of the regulatory system (e.g., tenure system) are similar (Luckert et al., 2011). Therefore, other provinces in Canada can learn from the experience of Alberta with respect to the impacts of forest management policies on productivity. Moreover, forest genomics research is being undertaken all over the world, especially in Canada, U.S., Brazil and Sweden where forestry is a key sector (Holliday et al., 2017). However, to the best of my knowledge, there is no study to date that has estimated the economic impact of increasing timber volume using genomic technology. The long term and public good nature of forest genomics research make it particularly challenging to quantify impacts and welfare changes (Hope et al., 2017). Lessons learned from this study could provide guidance for other regions interested in adopting genomic technology in the forest sector.

1.5 Thesis Organization

The remainder of the thesis is organized as follows. Chapter two estimates the rates of technical change and productivity growth in the Alberta logging industry over the period 1981-2012. In Chapter three, I assess the returns to R&D from GATB in Alberta. Finally, Chapter four presents a summary and implications from the previous chapters, lists some limitations of this research, and provides suggestions for future research.

Chapter 2: Technical change and productivity growth in the Alberta logging industry

2.1 Introduction

Strategic policy measures for maintaining the competitiveness of the forest sector should start at the timber harvesting stage of industrial production as the output of the logging industry (i.e., roundwood) is an important input for other forest-based manufacturing industries and a change of production structure in the logging industry has important implications for changes to the price of roundwood and other wood-based products (Kant and Nautiyal, 1997; Nanang and Ghebremichael, 2006). A more detailed investigation of the production structure would also reveal insights into the extent to which stringent forest regulatory policies in Alberta have slowed down technical change and negatively affected productivity in the sector. In addition, a stronger understanding of how the factors of production (i.e., capital, labour, materials and energy) are allocated and how the rate of technical change has evolved in the logging industry can contribute to better industrial investment decision-making and policy evaluation processes.

The purpose of this chapter is to investigate the production structure of the Alberta logging industry; specifically, we examine the nature of factor substitution, and estimate the rate of technical change (RTC) and total factor productivity (TFP) growth. I articulate options based on the empirical results that can help the Alberta government and private forest companies respond to current and future challenges facing the forest sector. I also discuss the potential impacts of current government regulations on the RTC and TFP growth, which can be informative to policy makers regarding future forest management policies.

The rest of the chapter is organized as follows: in section two, I provide a literature review of relevant studies. Next, I give a brief discussion of the production economic theory and empirical strategy used in this study. In section four, I describe the data sources and computation methods. I present the results in section five, and conclude the chapter with some discussion in section six.

2.2 Literature Review

At the national level, there have been studies examining both the logging industry and the lumber industry. Nautiyal and Singh (1985) investigate the production structure of the Canadian lumber industry using duality theory in production and cost and an iterative three-stage least-squares approach. In Nautiyal and Singh's (1985) study, they find that the production structure of the lumber industry is homogeneous and that factor inputs are fairly substitutable, assuming that the price of capital is equal to the rate of return on fixed assets. The main weaknesses of their study are that they only have 16 years of data and their assumption of Hicks neutral technical change is overly restrictive. In addition, they only calculate Allen elasticities of substitution, which forces factors to have symmetric elasticities of substitution. Kant and Nautiyal (1997) also use duality theory to examine the production structure of the Canadian logging industry. Empirically, they use an iterative Zellner method (Zellner, 1962) to estimate a translog cost function. Compared with a previous study (Nautiyal and Singh, 1985), Kant and Nautiyal (1997) use a longer time series (1963 to 1992), which allows them to test the null hypothesis of non-biased technical change. They also calculate Morishima elasticities of substitution, which are less restrictive than Allen estimates because they do not impose symmetry between pairs of factors. Kant and Nautiyal (1997) find the following results: the production structure of the Canadian logging industry is homogeneous; capital is more easily substituted by labour or energy than the reverse; there are substantial economies of scale; and lastly, regarding TFP growth, the effects of technical change dominate the scale effects (Kant and Nautiyal, 1997).

At the provincial level, there exist studies on each of the specific forest industries. Martinello (1987) estimates translog cost functions and calculate elasticities of substitution, technical change and returns to scale for British Columbia (BC) interior and coastal sawmills, planing mills, shingle mills, and plywood and veneer mills using pooled cross section time series data spanning 1963-1979. Due to a lack of capital expense and price data, Martinello specifies a constant returns to scale CES production function for capital services, which is then used to derive the price and the cost of capital. The results show that capital service and labour can be substituted for the increasingly scarce natural resources of timber (Martinello, 1987). However, the combined effects of factor substitution and technical change are not enough to offset the negative effects of declining size and quality of timber, and average costs increase over the sample (Martinello, 1987). Meil and Nautiyal (1988) analyze the intra-regional factor demand and production structure for four major Canadian softwood lumber producing regions (BC interior, BC coast, Ontario, and Quebec) using panel data covering the time period 1968-1984. The contribution of their study is that they estimate a more realistic quasi-fixed translog variable cost function by relaxing the total cost minimization assumption. This is because firms with nontransferable capital stock usually operate at less than full capacity in the short run and can only adjust the variable factors of production to cost minimization (Meil and Nautiyal, 1988). Meil and Nautiyal (1988) find that, generally, technical change is biased; specifically, it is material- and energy-using and labour-saving, indicating that any reduction in the wood supply or current wood quality level would discourage investment in currently employed technologies (Meil and Nautiyal, 1988). Nanang and Ghebremichael (2006) estimate a long-run translog cost function to analyze and compare production technologies in the timber harvesting industries of BC, Ontario, and Quebec using annual data from 1961 to 1999. They calculate the capital price using the perpetual inventory method developed by Christensen and Jorgenson (1969), which captures the effects of corporate income tax, investment tax credit, property tax, interest cost of the funds tied up in the physical asset, economic depreciation, and capital gains/losses due to changes in asset prices. Their results show that in general the substitution among all the factor inputs are inelastic, and the various industries have limited options to make input adjustments to changes in relative input prices. Similar to other studies, they find that technical change is biased toward being capital- and labour-saving and energy- and material-using (Nanang and Ghebremichael, 2006). Shahi et al. (2011) analyze the production technologies of logging, sawmill, veneer, plywood, and pulp and paper industries in Ontario using annual provincial data from 1967 to 2003. They also calculate capital price using the perpetual inventory method, and find that the logging industry in Ontario is non-homothetic; the own-price elasticity of materials and energy is relatively high for the logging industry, indicating the existence of input price flexibility and easier input substitution; and technical change is labour- and capital-saving but material- and energy-using.

Empirical studies on the link between policy stringency and productivity growth in the forest sector mainly focus on analyzing the economic effects of environmental regulations on productivity growth, but there is no ultimate consensus on whether the economic effects are positive or negative. The traditional approach sees public regulations that restrict the set of production technologies and outputs as burdens on economic activity because they raise costs of production without increasing output (Christainsen and Haveman, 1981). However, the Porter hypothesis claims that well-designed environmental policies can encourage innovation and improve the profitability and productivity which can outweigh the costs of the policies (Porter and Van der Linde, 1995). Boyd and McClelland (1999) report that environmental regulations in the American pulp and paper industry have positive effects on the productivity growth; while Hailu (2003) finds that most Canadian pulp and paper regional industries experience negative productivity growth once environmental regulations are imposed. Similarly, Broberg et al. (2013) find that investments in pollution abatement required by environmental regulations negatively affect the competitiveness of the Swedish pulp and paper industry. In terms of the economic effects of forest tenure policies on productivity growth, Niquidet (2008) finds that the Forest Revitalization Plan (FRP) in BC, which was implemented in 2003 and used to improve competitiveness and efficiency by providing greater flexibility to forestry firms, leads to lower returns for publicly traded forestry companies. The unintended consequence of the FRP is that it likely reduces supply security, thereby resulting in negative returns (Niquidet, 2008).

The existing literature has emphasized the forest sectors in provinces of Ontario, BC, and

Quebec, and uses relatively old data sets. No empirical study of the effects of public forest management policies on productivity growth has been undertaken. Though studies have criticized that forest management regulations in Alberta (and Canada) discourage innovation and hinder competitiveness (Haley and Nelson, 2007; Kant, 2009; Vertinsky and Luckert, 2010), there is no empirical evidence on how the rate of technical change and productivity growth have evolved over time. If both the rate of technical change and productivity growth have increased significantly over time, previous arguments on the effects of forest management regulations may not be valid. This study fills a gap in current knowledge of the production structure and technologies of the logging industry in Alberta, and allows us to examine how Alberta's comparatively strict forest management policies have affected productivity. The results of this study will shed light on the impact of government policies, and provide guidance on how to adapt to a more globally competitive environment.

2.3 Theoretical Framework

2.3.1 Estimation of the cost and factor demand system

Alberta forests are mostly publicly owned and regulated, with the key constraint being that the output levels of the logging industry are fixed by the annual allowable cut (AAC). Therefore, it is more appropriate to study the production structure by estimating a cost function (Kant and Nautiyal, 1997). In this study, I assume that all firms operate with the objective of cost minimization. According to duality theory and assuming several regularity conditions hold, the technical information of the underlying production function can be recovered from the parameters of the cost function if factor prices and output level of an industry are exogenously determined[1]. I further assume that the costs of production are weakly separable so that the aggregate production costs represent the production costs of a representative producer. This is a reasonable assumption for this study as the total costs can be separated into several stages: costs associated with accessing a stand (e.g., stumpage), costs associated

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[1] Labour, capital, and energy used by the logging industry constitute only small portions of their total use in the whole economy, so their prices can be taken to be determined outside the logging industry. Even though timber supply is heavily regulated by the government, it could be taken as perfectly elastic because the government shows little evidence of behaving like monopolists.

with harvesting (e.g., felling cost), and costs related to transportation (Mathey et al., 2009). Given this separability assumption, it is appropriate to use aggregate industrial-level data in lieu of firm-level data for this study.

The translog cost function approximates the true minimum cost function with a second order logarithmic Taylor series expansion around variable levels of output and input prices (Garcia and Randall, 1994). Following previous studies (Kant and Nautiyal, 1997; Nanang and Ghebremichael, 2006; Shahi et al., 2011), the translog function is specified as follows:

$$\begin{aligned} \ln C = {} & \ln\alpha_0 + \alpha_Q \ln Q + \sum \alpha_i \ln P_i + 0.5 \sum\sum \beta_{ij} \ln P_i \ln P_j + \sum \beta_{iQ} \ln P_i \ln Q \\ & + 0.5\alpha_{QQ}(\ln Q)^2 + \alpha_t T + 0.5\alpha_{tt} T^2 + \sum \beta_{it} \ln P_i T + \beta_{Qt} \ln Q T \\ & \qquad i, j = L, K, M, E \end{aligned} \tag{2.1}$$

where C is the total cost, Q is the output, P_i are the prices of the factor inputs, T is an indicator of time (e.g., state of technology), and α and β are coefficients to be estimated. For a cost function to be well behaved, it must be homogeneous of degree one in prices, given a certain output level. This implies the following set of restrictions:

$$\sum_i \alpha_i = 1,\ \sum_i \beta_{iQ} = 0,\ \sum_i \beta_{ij} = \sum_j \beta_{ji} = \sum_i \beta_{it} = 0 \tag{2.2}$$

These restrictions can be tested first by conducting a likelihood ratio test. Specifically, I first run the null model which is an unrestricted model and then run the alternative model which is a restricted model. A likelihood ratio test is conducted to identify which model has a better fit on the data. If the null model has a better fit, which means the above restrictions are not statistically satisfied, I can then impose the restrictions to ensure a theoretically consistent cost function (Kant and Nautiyal, 1997). I briefly discuss curvature, negativity and monotonicity properties later in the section on econometric results. There are three more testable hypotheses in terms of the underlying technology: homogeneity, homotheticity and returns to scale. For the translog cost function to be homothetic, it is necessary and sufficient that $\beta_{iQ} = 0$ $(i = K, L, M, E)$. Homogeneity of a constant degree in output occurs if the additional constraint $\alpha_{QQ} = 0$ occurs. The translog cost function exhibits constant returns to scale when another additional constraint, $\alpha_Q = 1$, is satisfied.

According to Zellner (1962), gains in efficiency can be realized by estimating a system of cost-minimizing input demand equations, which would be cost share equations in this case. An application of Shephard's Lemma yields a set of cost share equations of the form

$$S_i = \frac{\partial \ln C}{\partial \ln P_i} = \alpha_i + \sum_j \beta_{ij} \ln P_j + \beta_{iQ} \ln Q + \beta_{it} T \qquad i, j = L, K, M, E \tag{2.3}$$

where S_i is the cost share for each input. Since many of the coefficients in the cost function and share equations are the same, to achieve higher efficiency of estimation and obtain the estimates which only appear in the cost function (e.g., T), I simultaneously estimate the translog cost equation along with the cost share equations. Specifically, I estimate a seemingly unrelated regression (SUR) specification using Zellner's iterative procedure. Since the shares always sum to unity and only three of the share equations are linearly independent, I drop one share equation to avoid the singularity of the variance-covariance matrix when estimating the cost and factor shares system (Berndt and Wood, 1975). Stochastic estimation further requires the disturbance terms to be added to the cost function and the three share equations (Meil and Nautiyal, 1988). These errors are contemporaneously correlated across equations because input price changes cause changes in both cost shares and total cost. The equation disturbance terms are assumed to be normally distributed, with mean vector zero and constant covariance matrix. Lastly, the error terms are also assumed to be uncorrelated across time (Meil and Nautiyal, 1988).

2.3.2 Elasticity of substitution

Berndt and Wood (1975) demonstrated that for the translog cost function given by equation (2.1), it is straightforward to calculate Allen elasticities of substitution (AES) and price elasticities of demand for input factors using the following formulae:

$$\delta_{ij} = \frac{\beta_{ij} + S_i S_j}{S_i S_j}, \; i, j = K, L, M, E \tag{2.4}$$

$$\delta_{ii} = \frac{\beta_{ii} + S_i S_i - S_i}{S_i S_i}, \; i, j = K, L, M, E \tag{2.5}$$

$$\varepsilon_{ij} = S_j \delta_{ij} \tag{2.6}$$

$$\varepsilon_{ii} = S_i \delta_{ii} \tag{2.7}$$

Unlike the AES, the Morishima elasticities of substitution (MES) does not impose the symmetry condition and it is a sufficient statistic for assessing the effects of changes in price or quantity ratios on relative factor shares (Blackorby and Russell, 1989). According to Blackorby and Russell (1989), the MES can be calculated as follows:

$$M_{ij} = \varepsilon_{ji} - \varepsilon_{ii} \tag{2.8}$$

$$M_{ji} = \varepsilon_{ij} - \varepsilon_{jj} \tag{2.9}$$

2.3.3 Rate of technical change and total factor productivity growth

The translog cost function does not constrain technical change to be either constant or Hicks neutral. The rate of technical change (RTC) for a given cost function is

$$\frac{(-\partial \text{ln}C)}{\partial T} = -(\alpha_t + \alpha_{tt}T + \sum_i \beta_{it}\text{ln}P_i + \beta_{Qt}\text{ln}Q) \tag{2.10}$$

where α_t represents the constant rate of technical change; $\alpha_{tt}T$ represents the acceleration of the rate of technical change; $\sum_i \beta_{it}\text{ln}P_i$ represents input bias, and $\beta_{Qt}\text{ln}Q$ represents scale bias. A negative value for $\frac{\partial \text{ln}C}{\partial T}$ indicates that costs decrease with time as a consequence of technology improvement, while a positive value implies technology deterioration over time. Note that technical change is cost neutral if $\beta_{it} = 0$ because this implies that input cost shares do not change. When the underlying technology is homothetic, cost neutral technical change is equivalent to Hicks neutral technical change (Chambers, 1988).

TFP growth is a key driver of cost competitiveness and overall productivity. TFP measures the residual growth in outputs that is not accounted for by the growth in factor inputs (Solow, 1957; Jorgenson and Griliches, 1967), while TFP growth represents the difference between growth rates of aggregate output and aggregate input. The residual has been interpreted as technical progress (Denny et al., 1979) and other factors, such as scale, substitution, research and development etc. (Kant and Nautiyal, 1997). Denny et al. (1979) demonstrated that TFP growth can be expressed as the sum of scale effects and the RTC as follows:

$$TFPgrowth = \left(1 - \frac{\partial \mathrm{ln} C}{\partial \mathrm{ln} Q}\right) \frac{\partial \mathrm{ln}(Q)}{\partial T} - \frac{\partial \mathrm{ln} C}{\partial T} \tag{2.11}$$

The first term represents the scale effect and the second term represents the RTC (Denny et al., 1979). Under a cost-minimization setting where the production technology exhibits constant returns to scale, TFP growth is the same as the RTC.

2.4 Data and Empirical Analysis

I use time series data on the costs of labour, material and energy spanning 1981-2012 from Statistics Canada: logging industry (catalogue no.25-202 and CANSIM Table 301-0004). I use data on output for the period 1981-1996 from Statistics Canada (catalogue no.25-202), while data for the period 1997-2012 are from the National Forestry Database. This is because the statistical data on logging output is archived and has not been updated by Statistics Canada since 1996. The National Forest Database collects the provincial logging output data which has the same definition as the data from Statistics Canada. Therefore, it is appropriate to use the output data from the National Forest Database for the period 1997-2012. I describe how I construct and calculate my data on factor prices and capital cost in more detail below. Table 2.1 shows the summary statistics for the cost shares, factor prices, total costs and output level.

Table 2.1: Summary statistics of the cost shares, prices, total costs and output

Cost shares	Observation	Unit	Mean	Std. Dev.	Min.	Max.
Labour	32	-	0.17	0.04	0.11	0.25
Capital	32	-	0.25	0.06	0.13	0.35
Energy	32	-	0.05	0.02	0.03	0.11
Material	32	-	0.53	0.07	0.42	0.64
Deflated prices						
Labour	32	1000$	43.63	3.51	37.69	49.59
Capital	32	price index	0.41	0.08	0.34	0.59
Energy	32	price index	102.34	20.64	79.21	151.01
Material	32	price index	98.68	19.23	75.81	148.63
Total cost	32	1000$	499747.1	244105.8	154063.5	858762.6
Total output	32	1000m^3	17538.88	6485.72	5714	27546

2.4.1 Prices of labour, energy, and material

I calculate the implicit price of labour by dividing the total costs (salaries plus wages) by the total number of employees. I use data on total number of employees from Statistics Canada: logging industry (catalogue no.25-202 and CANSIM Table 301-0004). The price of energy is represented by the energy price index in Alberta, and I use the price index data from CANSIM Table 026-0020. I use the raw material price index of wood as the price of material because more than 90% of the materials used in the logging industry is standing timber (Kant and Nautiyal, 1997). Lastly, the data on timber price is from CANSIM Table 330-0007.

2.4.2 Capital cost and price

Cost and price of capital data for the Alberta logging industry are not available. Following Ghebremichael et al. (1990), I adopt a value-added approach to derive capital cost. I calculate the value of capital cost by subtracting the cost of manufacturing labour from the value-added in manufacturing activities, using the value-added data from Statistics Canada: logging industry (catalogue no.25-202 and CANSIM Table 301-0004). I calculate the service price of capital using the perpetual inventory method to reflect the opportunity cost of an asset, as given by its rental or service price (Christensen and Jorgenson, 1969). In this study, capital input is aggregated into three types of assets: buildings, machinery and equipment, and engineering. I compute the annual rental prices for these three types of assets individually and then calculate the arithmetic average of the three asset prices to obtain an overall rental price of capital using the following formula:

$$R_t = \frac{(1 - K_t - U_t * Z_t)}{1 - U_t}(q_{t-1} * p_t + q_t * d_t - n_t * q_t) + \phi_t * q_t \tag{2.12}$$

where R_t is the rental (service) price for capital at time t; K_t is the investment tax credit rate in year t, which is obtained from the Canada Revenue Agency; U_t is the provincial corporate income tax rate in year t, which is from the Alberta Treasury Board and Finance, Tax and Revenue Administration; Z_t is the present value of depreciation deductions for the purpose of taxation on a dollar's investment, which can be calculated as $Z_{i,t} = \delta_{it}\frac{(1+p_t)^{0.5}}{p_t+\delta_{it}}$, where δ_{it} is the capital cost allowance depreciation rate for the ith capital asset at time t; q_t is a capital-asset price index at time t, which is calculated as the ratio of the value of the asset in current dollars to the value of the asset in constant dollars (Nanang and Ghebremichael, 2006; Shahi et al., 2011). The data on value of assets are from CANSIM Table 031-0005; p_t is the cost of financing capital, represented here by Government of Canada marketable average bond rate at time t (CANSIM Table 176-0043); d_t is the physical rate of depreciation of a capital asset at time t, which is calculated using the double declining method (Nanang and Ghebremichael, 2006; Shahi et al., 2011); n_t is the capital gains rate at time t which is included to account for the capital gains or losses due to changes in prices of the assets, and it is calculated as a 5-year moving average of the natural logarithm of the asset price, or $n_t = \frac{ln\frac{q_t}{q_{t-5}}}{5}$; ϕ_t is the property tax rate at time t. Property tax rates are not included as they are not widely available. However, since buildings represent less than 1% of the total capital expenditures in the Alberta logging industry, the property tax rates are expected to have a negligible impact on the rental price value.

2.5 Results

I test six different restrictions of the long-run translog cost function to identify which model best fits the technology of the Alberta logging industry. Model 1 is the unrestricted, complete, total cost function. Model 2 tests for Hicks neutral technical change, while Model 3 tests for the null hypothesis of no technical change. Models 4 and 5 test for homotheticity and homogeneity, respectively. Finally, Model 6 restricts the elasticity of substitution of the cost function to unity. I use a log-likelihood ratio test to select the model that best represents the production structure of the Alberta logging industry. Table 2.2 reports the results of the log-likelihood ratio tests.

Table 2.2: Log-likelihood ratio tests of restrictions on translog cost functions

Model type	No. of restrictions	Log likelihood ratio (calculated χ^2-values in parenthesis)	
		Alberta	Critical χ^2
Unrestricted		286.7	
Hicks neutral technology	3	271.5 (30.5)***	11.345
No technological change	6	232.1 (109.3)***	16.812
Homothetic	3	282.8 (8.0)	11.345
Homogeneous	4	243.6 (86.3)***	13.277
Unitary elasticity of substitution	6	261.7 (50.0)***	16.812

† *, **, ***indicates that the estimates of the corresponding parameters are statistically significant at 10%, 5%, 1% significance level, respectively.

The production structure of the Alberta logging industry is found to be homothetic, indicating that the input proportions depend only on the input price ratios. Previous studies find the production structure of the Canadian logging industry (Kant and Nautiyal, 1997), BC and Quebec logging industries (Nanang and Ghebremichael, 2006) to be both homothetic and homogeneous, and the Ontario logging industry to be non-homothetic (Nanang and Ghebremichael, 2006; Shahi et al., 2011). Consistent with previous studies (Kant and

Nautiyal, 1997; Nanang and Ghebremichael, 2006; Shahi et al., 2011), the null hypotheses of Hicks neutral technical change and no technical change are rejected, indicating that technical change does exist and it is biased. Unitary elasticity of substitution is also rejected. Therefore, the production technology cannot be approximated by a Cobb–Douglas production function.

Table 2.3: Estimated parameters of the homothetic translog cost function of the Alberta logging industry

Coefficients	Parameter value (standard error)	Coefficients	Parameter value (standard error)
α_0	0	β_{KM}	0.0449 (0.0224)*
α_Q	2.785(0.286)***	β_{KE}	-0.013 (0.0301)
α_{QQ}	-0.466(0.061)***	β_{ME}	-0.0604 (0.014)***
α_L	-0.460(0.145)***	β_{LQ}	-
α_K	0.760(0.242)***	β_{KQ}	-
α_M	0.700 (0.125)***	β_{MQ}	-
α_E	0.000176(0.153)	β_{EQ}	-
β_{LL}	0.218 (0.031)***	α_t	-0.633 (0.102)***
β_{KK}	0.133 (0.048)***	α_{tt}	-0.0085 (0.0014)***
β_{MM}	0.132 (0.023)***	β_{Lt}	-0.0047 (0.0008)***
β_{EE}	0.0103 (0.028)	β_{Kt}	0.0043 (0.0013)***
β_{LK}	-0.165 (0.029)***	β_{Mt}	-0.0014 (0.00102)
β_{LM}	-0.116 (0.0185)***	β_{Et}	0.0017 (0.0009)**
β_{LE}	0.0628 (0.022)***	β_{Qt}	0.092 (0.0127)***

† *, **, ***indicates that the estimates of the corresponding parameters are statistically significant at 10%, 5%, 1% significance level, respectively. Standard errors are in parentheses.

Table 2.3 presents the parameter estimates of the selected cost function (model 4). The restrictions of linear homogeneity, adding up and symmetry are imposed on the estimated cost function. A well-behaved cost function is also concave in prices with the concavity condition satisfied if the Hessian matrix of the second-order partial derivatives is symmetric and negative semi-definite (Varian, 1992). I checked these curvature conditions locally and found them to be satisfied [2].

2.5.1 Elasticity of substitution and price elasticities

The Allen elasticities of substitution (AES) and Morishima elasticity of substitution (MES) results at the mean level of input shares are summarized in Table 2.4. In general, AES estimates are greater than MES estimates in absolute terms. Since MES is a better measurement of the elasticity of substitution, I only analyze the MES results here. The MES results suggest that limited substitution opportunities exist between factors of production, though most of the estimated elasticities of substitution are statistically insignificant at the 1% significance level[3]. Energy and labour are relatively more substitutable among all the input pairs, indicating that as energy price increases, more labour can be used in place of energy. The high substitutability of labour and energy, together with the fact that the mean energy cost is only about 5% of total production costs, suggests that a change in energy price should not have a significant impact on the production process as firms can substitute it with labour. The MES also suggests that material is not easily substituted by labour or capital, and material has a complementary relationship with energy. Given this limited substitutability of material and other inputs and the fact that the mean material cost share is more than half, it can be beneficial to invest in technologies that reduce timber resource cost or invest in capital that can process timber more efficiently to yield a higher quantity of wood products.

I present results of the own- and cross-price elasticities of demand for inputs in Table 2.5. In general, the own-price demand elasticities are inelastic. I find that the own-price demand elasticity for labour has a theoretically inconsistent positive sign and it is statistically significant at 10% significance level. This may be due to sampling error and may not reflect the characteristics of the whole population. The negative signs of the cross-price demand elasticities indicate complementary relationships between input pairs. With the exception of the cross-price demand elasticity for energy with respect to labour price, most inputs

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[2] I randomly selected some points and then calculated the Hessian matrix and principle minors manually.

[3] I used the delta method to calculate the standard errors used in the tests of statistical significance.

Table 2.4: Estimated Allen and Morishima elasticities of factor substitution for the Alberta logging industry, 1981-2012

	Morishima elasticities of substitution				Allen elasticities of substitution			
Factor Input	Labour	Capital	Material	Energy	Labour	Capital	Material	Energy
Labour	-	-0.8***	-0.3*	1.1**	1.4*	-2.6***	-0.1	7.0***
Capital	-0.4	-	0.2	0.2	-2.6***	-0.8	1.4***	-0.1
Material	0.2	0.2	-	0.4	-0.1	1.4***	-0.4***	-1.3**
Energy	1.1*	0.7	0.7	-	7.0***	-0.1	-1.3	-14.5

† Row and column represent numerator and denominator of elasticity respectively. For example, the elasticity of substitution of labour by capital is in the row corresponding to labour and the column corresponding to capital. *, **, *** indicates that the estimates of the corresponding parameters are statistically significant at 10%, 5%, 1% significance level, respectively.

are cross-price inelastic. This means for most of the input factors, a price change in one input will not affect the demand for other inputs significantly. These results regarding price elasticities are similar to the results found by previous studies (Kant and Nautiyal, 1997; Nanang and Ghebremichael, 2006; Shahi et al., 2011). My results also suggest that energy is most responsive to the price of labour (cross price elasticity=1.416). Specifically, a 10% increase in the price of labour will lead to a 14% increase in the demand for energy during the production process.

Table 2.5: Estimated price elasticities for the Alberta logging industry, 1981-2012

Factor Input	Labour	Capital	Material	Energy
Labour	0.284*	-0.588***	-0.059	0.364***
Capital	-0.517***	-0.193	-0.041	-0.0041
Material	-0.023	-0.018	-0.228***	-0.065**
Energy	1.416***	-0.018	-0.649**	-0.748

† Row and Column represent numerator and denominator of elasticity respectively. For example, the elasticity of demand of labour with respect to capital price is in the row corresponding to labour and the column corresponding to capital. *, **, *** indicates that the estimates of the corresponding parameters are statistically significant at 10%, 5%, 1% significance level, respectively.

2.5.2 Rate of technical change and total factor productivity growth

The most striking finding is that the rate of technical change (RTC) is negative for most of the years in my sample (Figure 2.1). However, this result is not surprising when you consider that only 26% of Canadian logging firms engage in research and development (R&D) (Schaan and Anderson, 2002). This is considerably lower than in other forest sector industries. Kant and Nautiyal (1997) find similar negative RTC for the Canadian logging industry, Nanang and Ghebremichael (2006) for the BC logging industry, and Shahi et al. (2011) for the Ontario logging industry. According to Madore and Bourdages (1992), while the pace of technological change in the forest industry has been stepped up virtually everywhere in the world, fewer and fewer Canadian forestry companies compete on the cutting edge of technological change. This is caused by a number of factors including the lack of technological expertise, low manpower levels in the R&D field, the lack of technology transfer mechanisms, and insufficient government incentives (Madore and Bourdages, 1992). Additionally, regulations may negatively affect the adoption of new technologies. For example, the 10-axle log truck was invented to reduce the transportation cost of logging firms by increasing payload and reducing the amount of traffic. However, bridge weight restrictions in some areas in Alberta tend to discourage the adoption of increased axle configurations (Kryzanowski, 2009).

It should be noted that the RTC in this study may be under-estimated for three possible reasons: 1) as logging sites move to more difficult areas far from factories and roads, the productivity of logging operations may decline due to the increase in labour and capital costs (Kant and Nautiyal, 1997); 2) declining timber quality in Alberta may reduce the productivity of new logging technologies. Since 1995, more and more logging firms in Alberta adopt the more advanced cut-to-length logging system from Europe (Pulkki, nd). However, research shows that low quality trees (e.g., trees with large branch) can reduce cut-to-length harvesting productivity by 15 to 20% (Labelle et al., 2016); 3) forest companies may harvest uneconomically due to "use-it-or-lose-it" policies. These policies are intended to maximize industrial development by forcing a firm to fully use the public forests allocated to it for timber production; otherwise its allowable cut level may be reduced (Anderson et al., 2012). To maintain their harvestable area, forest companies may harvest more than the economically desirable level in some years. Anderson et al. (2012) find that there are significant costs associated with "use-it-or-lose-it" policies. Therefore, the productivity of logging operations may decline due to the increase in material costs caused by stringent policies. In the estimated cost function, the input factor bias coefficient is negative for labour and positive for capital and energy. Thus, technical change is labour-saving, but capital- and energy-using. Even though the coefficient for material is negative, it is statistically insignificant. Therefore, technical change is material-neutral over time. Future innovations might want to focus on material-saving technical change as future wood supply growth potential is predicted to be limited. Virtually all forest lands suitable for forest industry development have been allocated in Alberta and there are continuing pressures to reallocate lands from timber production to other uses such as industrial and municipal development, recreation, and conservation purposes (Franceschi, 1998; Government of Alberta, 2014).

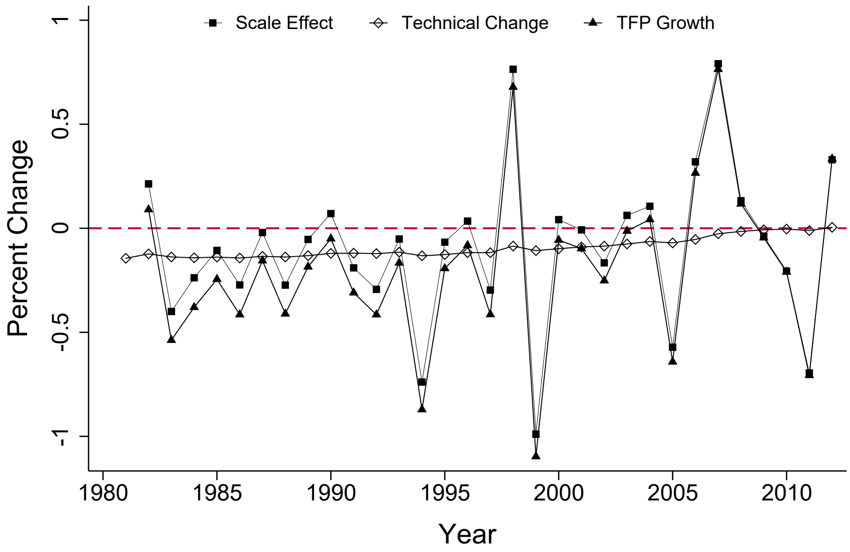

Figure 2.1: Components of total factor productivity (TFP) growth

The translog function allows for both positive and negative scale effects [4]. The elasticity of scale is a measure of return to scale which is equal to the inverse of the cost elasticity $\left(\frac{\partial \ln C}{\partial \ln Q}\right)^{-1}$. Since $\frac{\partial \ln Q}{\partial \ln C} = \frac{\partial Q}{\partial C}\frac{C}{Q} = \frac{AC}{MC}$, a scale elasticity greater than, equal to, or less than one implies increasing, constant, or decreasing returns to scale, respectively. In the

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[4] Scale effect is expressed as $\left(1 - \frac{\partial \ln C}{\partial \ln Q}\right)\frac{\partial \ln Q}{\partial T}$.

estimated cost function, the estimated scale elasticity is 1.1 for the Alberta logging industry when evaluated at the means of the samples. Therefore, the impact of scale effect on the total factor productivity (TFP) growth will depend on whether the output has increased or decreased over time. The estimated scale elasticity for the Alberta logging industry is low compared with results obtained by Kant and Nautiyal (1997) for the Canadian logging industry (2.4), Nanang and Ghebremichael (2006) for Canadian timber-harvesting industries (2.17 for BC, 1.55 for Ontario, and 1.44 for Quebec); however, it is similar to the result obtained by Shahi et al. (2011) for the Ontario logging industry (1.02). Figure 2.1 shows that in only a small number of years are the scale effects able to compensate for the negative effects of technical change as output increased from the preceding year for only short periods of time. Also note that the first scale effect spike around 1997 is likely due to industry expansion. According to Franceschi (1998), from 1986 to 1996, encouraged by the abundant timber supplies and new hardwood processing technology and markets, the Alberta government invested $5 billion in the forest sector which led to the establishment of pulp mills and panel plants. Furthermore, in Canada, major producers of pulp and paper products are frequently integrated to include logging activities (Globerman et al., 1999), thereby resulting in an expansion of the logging industry. Around 2006, the mountain pine beetle spread from BC and infested thousands of trees in northern Alberta (Government of Alberta, 2017). Therefore, the second scale effect spike around 2009 may have been caused by the salvage harvesting policies in Alberta.

In most years, even though the RTC has an increasing trend, TFP growth has been slightly negative. In general, the scale effect dominates the TFP growth since the lines representing the scale effect and TFP growth have very similar patterns and the magnitude of the RTC is relatively small, especially during the period 2005-2012. In theory, the Alberta logging industry can make use of economies of scale through directing wood supply from a wide area to central, large processing plants to help in reducing production costs and increasing TFP growth. However, the mill appurtenancy requirement, which requires tenure holders to own and operate wood processing facilities, directs timber to specific mills and tends to prevent tenure holders from achieving economies of scale (Vertinsky and Luckert, 2010). This is another example of how government policies can have negative economic effects on TFP growth.

In summary, the negative values for RTC and TFP growth indicate weak productivity growth and diminished competitiveness in the Alberta logging industry. One possible explanation for this is Alberta's stringent harvesting policies, such as the "use-it-or-lose-it" policies, which may have negative effects on the RTC. On the other hand, investments in the forest sector, such as establishing new mills and plants, can lead to positive scale effects. Therefore, both harvesting policies and investment decisions can significantly affect TFP growth. I discuss the implications of my results and provide some recommendations in the next section.

2.6 Discussion and Conclusions

In this chapter, I analyze the production structure of the Alberta logging industry, and estimate elasticities of input substitution, cross- and own-price elasticities, RTC, scale effect, and TFP growth. Results indicate that the production structure of the Alberta logging industry is homothetic which means the output level has no effect on the input use as long as relative prices remain constant. The estimated MES suggest that the Alberta logging industry has very limited options to substitute among pairs of input, especially material (wood) which enters into the output (logs) in fixed proportions. Technical change is labour-saving, capital- and energy-using, and material-neutral. Lastly, and most importantly, I find small positive scale effects and negative RTC that together contributed to negative TFP growth during my study period. The results of my study provide some evidence that Alberta's stringent policies have reduced the incentive for the forest industry to improve its overall productivity. My results also indirectly lend support to earlier work that suggests regulatory constraints on the forest sector have increased the costs of production and decreased profits (Clarke, 1997).

One obvious strategy to increase TFP growth and maintain a strong competitive position in the world market is to devote more resources to R&D. This R&D investment can lead to a higher quantity and quality of raw materials, which is the single largest cost and the least substitutable input. However, the current forest tenure system creates disincentives for industrial investment and innovation (Haley and Nelson, 2007; Vertinsky and Luckert, 2010). For example, regulations on international and inter-provincial shipments and exports of unprocessed logs reduce the value of domestic timber, thereby reducing the incentive for firms to invest in silviculture and high wood-use efficiency technologies (Luckert and Haley, 1993). In addition, restrictions on using non-native seeds on public land in Alberta discourage forest companies to invest in tree improvement programs (Anderson et al., 2015). These specific policies in combination with the private-public nature of forest land in Alberta create an environment in which private firms have little incentive to invest in R&D. These policies have ultimately led to a stagnant forest sector that has seen its global competitiveness eroded as other countries have adopted policies that have led to greater productivity increases in the sector.

For comparison purposes, let's consider one of Canada's main competitors-namely Sweden, where the climate is somewhat similar to Canada's but the forest management policies are very different. In Sweden, more than 80% of forests are privately owned and the 1993 Forestry Act simplified rules and regulations leading to a more results-based approach instead of the command and control approach which is currently used in most Canadian provinces (McDermott et al., 2010; Bergquist and Keskitalo, 2016). Moreover, instead of using administratively set timber prices like most of Canadian provinces, timber sale arrangements in Sweden are made through bilateral negotiations between buyers and sellers (Kant, 2009), which creates a more competitive timber market. While the U.S. and Canada may have experienced higher TFP growth than Sweden during the period 1970-1980 (Oum et al., 1990), a more recent study with data covering the period 1971-2005 shows that Sweden's sector has seen higher TFP growth than its North American counterparts (Hussain and Bernard, 2017). While one cannot infer that Sweden's policies directly caused greater productivity, this example does highlight the fact that there is room for Canadian governments to influence technical change that targets timber production and wood processing by providing the right incentives for forest companies. For example, policy reforms such as removing minimum cut and log export controls, and allowing hybrid or exotic tree species to be planted on public land could potentially help increase investment in R&D and achieve productivity growth (Vertinsky and Luckert, 2010; Anderson et al., 2015).

While forest companies need policy incentives to invest in R&D, governments also need incentives to reform forest policies. The potential negative impact of policy reforms, such as possibly increasing unemployment in the short run due to a more competitive log market, may discourage governments from changing current policies. Therefore, forest companies and governments need to work together to create scenarios that are both economically and socially beneficial. For example, forest companies can take initiatives to convince governments that what they want to do can meet higher order objectives with respect to both economic and environmental goals. Such a results-based approach may not only allow firms more discretion in how they achieve forest management goals but also help governments achieve higher social benefits.

Chapter 3: Returns to genomics-assisted tree breeding R&D

3.1 Introduction

A growing global population, increased competition, and a changing climate are some of the challenges facing the agriculture and forest sectors in Canada. Consequently, the need to improve productivity is paramount to maintaining global competitiveness. R&D in animal and plant breeding has resulted in higher yields for producers, and significant investments in genomics research in the past two decades could yield even greater gains in the near future. The literature on the economic impact of genomics-based technologies in the agriculture and forest sectors is small, but two recent studies include Weaber and Lusk's (2010) study on the economic value of improving beef tenderness using genomics (specifically, genetic markers) and Naseem and Singla's (2013) study on the economic impact of identifying novel traits in canola using genomics. Both studies found sizable benefits from using genomic technology to select for economically beneficial traits. While the forest sector has been slower to adopt the technology, it is uniquely suited to benefit from genomic technology because of its long breeding horizons. Traditional tree breeding in boreal regions takes about 30 years to finish one breeding cycle, making it difficult to respond quickly to external changes (e.g., climate change, new regulations and changes in the market). With the use of genomic technology, the tree breeding cycle can be significantly shortened: by up to 20 years in some cases. Moreover, genomic selection delivers more accurate breeding values which allows breeders to achieve higher genetic gain per breeding cycle (Porth et al., 2015; Ratcliffe et al., 2017).

Though the benefits of genomic technology have been widely recognized, to date, no forest products company in Canada has adopted genomic technology into mainstream business activity (Porth et al., 2016). This may be due to the current stringent forest management framework and lack of evidence on industrial benefits of adopting the technology. In particular, the role of the "allowable cut effect" (ACE) has diminished the incentive to invest in new productivity-enhancing technologies, such as genomics. While the idea of an ACE has been around in Canada since the 1990s, under the enhanced forest management policy framework, the ACE has been largely unsuccessful (Luckert and Haley, 1995).

The primary objective of this chapter is to estimate the economic returns of adopting genomic technology in the Alberta forest sector and the extent to which the ACE policy will affect the economic returns to GATB R&D. The presence of AAC constraints and forced vertical integration in Alberta suggests that analyzing the price responsiveness of timber supply to stumpage prices is inappropriate (Luckert and Alavalapati, 1995). Instead, investigating a timber supply change and then translating that timber supply change into a forest product supply change and exploring the forest product market is more meaningful. Therefore, I propose a two-step approach for estimating benefits brought about by genomics research in forestry. The first step is to quantify the increase in harvest volume attributable to TB or GATB research through a timber supply simulation model, holding all other production parameters constant. The second step is to integrate the timber supply change information into a global forest product trade model which is developed and used to measure the economic surplus gain. My judgments about economic performance are made from the viewpoint of society (i.e., sum of consumer and producer surplus) rather than individual forest owners (the governments) or producers. The criterion I adopt for assessing the welfare effects of using genomic technology is a comparison of the net gain, the surplus of benefits over costs, that accrues to society as a whole over several scenarios.

The findings of this study are useful in guiding investment decisions on genomic technology and policy decisions on the use of the ACE policy instrument in Alberta. While genomic technology offers numerous improvements upon traditional methods, the overall welfare effect in response to the uptake of genomic technology by the forest companies and the use of the ACE by the government in the tree improvement context are uncertain. On the one hand, the government may not want to support this productivity-enhancing technology. This is because the technology that increases timber supply may result in price and producer profit decreases and the benefits to consumers may mainly accrue to foreign consumers, as most forest products in Canada are destined for exports. On the other hand, with a large inventory of forest resources, Canada has a strategic interest in ensuring sufficient timber supply in the market and therefore preventing a rise in price that might induce a permanent substitution of wood products (Gaston et al., 1995). In this case, public resource owners in Canada may want to support R&D that increases forest productivity (e.g., faster-growing trees) (Gaston et al., 1995). Given the above dilemma facing the decision-makers, an assessment of the returns to genomics R&D can reveal the conditions under which the adoption of genomic technology and the implementation of the ACE policy are beneficial.

The following section is a review of the forest economics literature concerning the ACE policy, the economic evaluation techniques of a research program and economic impact analysis of timber and wood products market shocks. Section three introduces the model and model parameterization, section four presents the simulation scenarios, and section five reports estimation results. I wrap up with a discussion of implications in section six.

3.2 Literature Review

3.2.1 Allowable Cut Effect

Schweitzer et al. (1972) first define ACE as an "immediate increase in today's allowable cut which is attributable to expected future increases in (timber) yield." In the U.S., ACE has been used in economic analysis to evaluate returns on public investment. Researchers later argue that using ACE to measure returns to federal timber investment may overestimate the rate of return and creates economic distortions in the budget allocations of public forest management agencies because the returns are influenced by both real productivity effects and by administratively determined policies relating to rates of harvest (Teeguarden, 1973; Lundgren, 1973). However, in Canada, as managing public forests is generally a direct responsibility of the private sector, ACE has been the major policy instrument used by the Canadian provinces to encourage private investments in silviculture on Crown forests (Luckert and Haley, 1995). In the Canadian context where forest management practices of the private sector are subject to stringent public sustainable forest management policies and the even-flow constraint has been carefully chosen to meet certain well-defined social goal, ACE has a legitimate role in timber investment analysis because the use of ACE can reduce the opportunity cost of the sustainable yield policy (Binkley, 1980).

Relatively few studies have explored empirically the economic incentives created by ACE for forest companies. Based on an empirical forest level study, Hegan and Luckert (2000) show that only in limited cases, there are positive returns for silviculture investments and therefore little incentive exists for forest companies to undertake ACE investments (Hegan and Luckert, 2000). Their study only focuses on certain specific silviculture activities (i.e. extensive and intensive forest management) and thus, the results of their study are not generally applicable to all the silviculture investments. The effectiveness of the ACE might be different if different silviculture activities are considered.

3.2.2 Standard Economic Evaluation Techniques

Based on the welfare concept, the net benefits of a research project is usually calculated from considering the research benefit over what would have occurred in its absence, net of the costs of doing the research (Heisey et al., 2010). The econometric method and the economic surplus method are two major methods commonly used to measure the benefits and costs of research through constructing appropriate counterfactual scenarios. The econometric analysis relates the measure of costs to the measure of benefits via statistical estimation while economic surplus analysis relates costs to benefits synthetically (Heisey et al., 2010).

Econometric approaches require the estimation of econometric models, either through direct estimation of production functions or indirect estimation of profit or cost functions, to infer the impact of research on output or productivity. Hyde et al. (1992) use the econometric method to evaluate the economic benefits of forestry research. Their approach begins with industry production as a function of public and private research expenditures, and other productive inputs. Supply and demand functions are derived from a profit function using Hotelling's lemma. The system of supply and demand equations are then simultaneously estimated using time series data on research expenditures and input prices. Their model permits direct estimation of not only the net economic benefit but also the value of the marginal product resulting from research, which gives the addition to output originating from the last unit of research. Gopinath and Roe (2000) use the cost function approach to analyze research spillover and returns to agriculture R&D in three vertically linked U.S. sectors: food processing, primary agriculture, and farm machinery and equipment. Their model leads to a system of 12 nonlinear equations. Gopinath and Roe's procedure allows them to estimate private and social rates of return on research in each sector under scenarios with and without taking research spillovers from sector to sector into account. The potential problems with the econometric approaches lie in extensive demands they place on data and the fact that the approaches are confined to more aggregated data. The econometric approaches are also primarily used for *ex post* analysis.

Economic surplus approaches mainly look at how research affects supply, demand, and their resulting market outcomes. Benefits from research are measured by changes in areas that are defined as consumer and producer surpluses. The gain in surplus can then be compared against the costs of the research. Barkley (1997) analyzes the *ex post* economic impact of the wheat breeding program at the Kansas State Agricultural Experiment Station by modifying an economic surplus model from Alston et al. (1995). The author constructs a two-sector model consisting of Kansas and the rest of the world. Barkley (1997) finds that the major beneficiaries of Kansas wheat improvement research are Kansas wheat producers who adopted the new varieties. Naseem and Singla (2013) analyze the *ex ante* economic impact of novel traits in canola resulting from the use of genomic technology. The changes in welfare are calculated based on a stochastic economic surplus model (Alston et al., 1995). They find that the major beneficiaries of the surplus gain are consumers as well as Canadian producers and innovators. They also find that net benefits are sensitive to supply elasticity and R & D lags (Naseem and Singla, 2013). The economic surplus model does provide us with a relative easy way to calculate the economic surplus gain brought by a new technology or return to R&D, and it is very useful in estimating the distribution of benefits among different stakeholders. The economic surplus method can be used for *ex ante* as well as *ex post* research evaluation. The main limitations of economic surplus models include the assumptions about the exogenous parameters and little attention on the dynamic issues. Since the surplus results are calculated directly using the exogenous parameters (e.g., elasticities), the accuracy of the results depends highly on the accuracy of the magnitude of the parameters. I adopt the economic surplus method in this study in the sense that the demand and supply curves are calibrated instead of being econometrically estimated. As a reduced form static model, the economic surplus model might not be able to capture the real behaviors that are happening in the marketing process, and the dynamic issues are put aside.

3.2.3 The Impacts of Market Shocks in the Forest Sector

The spatial equilibrium (SE) model is commonly used to estimate the demand and supply curves and assess the effects of product market shocks in the forest sector. The advantage of the SE model is that it is able to predict the new trade patterns easily over a long-term period by maximizing the total trade surplus (Adams and Haynes, 1987). The SE model also allows us to perform policy analysis under different scenarios by simply altering the parameters in the objective function or constraints.

Delcourt (1995) uses a partial equilibrium trade model to examine the effects of forest policies on international trade flows of softwood lumber (SWL) and predict changes in SWL production, consumption and prices for seven demand regions and eight supply regions over a 38-year period from 1987 to 2025. In the study, Delcourt (1995) considers two scenarios: 1) a decrease in British Columbia (BC) production; and 2) an increase in supplies from alternative sources. Results of the first scenario suggest that BC would experience a net increase in welfare at little expense to its domestic consumers in the short-run due to the increased global SWL price and redistribution of exports (Delcourt, 1995). Under the second scenario, producers in BC are not significantly affected by the lower prices; revenues of BC producers are actually increasing overtime (Delcourt, 1995). Abbott et al. (2009) further extend Delcourt's approach by incorporating uncertainty of parameters into the spatial equilibrium model, which is used to analyze the economic effects of Mountain Pine Beetle (MPB) outbreaks on the BC forest industry. Abbott et al. (2009) divide the world into 21 regions and they use the model to project the production, consumption, and trade flows in sawlogs and lumber from 2005 to 2035. Instead of exogenously shifting the intercept of the lumber supply curves, Abbott et al. (2009) adjust the AAC over time to reflect the impact of MPB outbreaks on timber supply. The results indicate that the timber shortage caused by MPB would negatively affect both the BC interior timber and lumber sectors in terms of producer surplus (Abbott et al., 2009). Their results also suggest that the timber shortages would lead to a greater loss for the lumber manufacturing sector than the timber sector because the timber shortage creates quota-like rents for the timber sector, while there was only cost increases in the lumber sector (Abbott et al., 2009). The main weakness of these two studies (Delcourt, 1995; Abbott et al., 2009) is that they do not account for the differentiated forest products and substitutes. Their models are also not real dynamic models in the sense that capital investment and harvesting decisions are not endogenous.

Chang and Gaston (2014) use a recursive dynamic spatial equilibrium model to analyze the competitiveness of the Canadian SWL industry. The main contribution of their paper is that they relax the restrictive assumption of product homogeneity and disaggregate SWL into higher and lower grade lumber groups. Using data in 2011 as starting values, the authors make assumptions about future demand and supply based on factors that may affect global SWL markets and projected global SWL trade flows from 2012 to 2021. Their results indicate that for both Canadian high grade and low grade SWL, in the near future, the annual total exports would decline significantly; SWL price would increase globally and the price increase for lower grade SWL would be greater than for higher grade lumber (Chang and Gaston, 2014). Using similar spatial equilibrium modeling techniques, Chang and Gaston (2015) examine the global impacts of potential changes in trade policies and supply constraints in Russia and New Zealand. They find that, compared to the baseline projection, the Russian softwood log export tax reduction would cause an increase in Russian log production, exports and prices over the 2012–2021 period. On the other hand, restricting New Zealand's log production would cause both export and annual production in New Zealand to drop. The weaknesses of the two papers are that the lumber supply changes are all based on assumptions, and therefore the accuracy of the simulation results depended on the accuracy of the assumptions. In their studies, changes in timber supply and harvesting decisions in different regions are also not considered (Chang and Gaston, 2015).

The purpose of this study is to extend the previous economic analyses by explicitly considering the impact of accelerated forest growth, resulting from the use of genomically-improved reforestation materials, on harvesting decisions (i.e. annual allowable cut) and forest product markets through a timber supply model and an economic model. Methodologically, the economic model used in this study has drawn heavily on the spatial equilibrium model developed by Chang and Gaston (2014) and Gaston and Marinescu (2006). Chang and Gaston (2014), using 2011 as the base year, perform a national level analysis; and the focus of their study is to project the future production, consumption and trade flows of lumber in different regions. However, the purpose of my study is to analyze the welfare effects of adopting genomic technology in the Alberta forest sector using a more updated data set. In short, this study differs in scope and in methodology from all other studies previously conducted on the forest sector.

3.3 Model and Model Parameterization

3.3.1 Timber Supply Model

Alberta's commercial forests are primarily on Crown land and the right to harvest Crown timber is allocated to companies and individuals through an area- or volume-based tenure system (Alberta Agriculture and Forestry, 2018). Though most production is organized and carried out by private entrepreneurs responding to market incentives, they are strongly influenced and constrained by decisions and regulations of the Alberta government. The government practices sustainable forest management, which aims to provide a steady timber supply for operating forest companies and ensure forest values are maintained for future generations (Alberta Agriculture and Forestry, 2018). Forest companies are responsible for the management of the forest within their respective Forest Management Agreement (FMA) areas. Forest Management Plans (FMP), which are submitted and renegotiated every 10 years, are a requirement of FMAs (Alberta Agriculture and Forestry, 2018). Each FMP covers a forest planning horizon of 200 years and includes detailed information of where, when and how trees on Crown land will be harvested and managed (Alberta Agriculture and Forestry, 2018). In FMPs, linear programming has been used extensively to characterize the dynamics of forest production and develop strategic forest management plans, especially for large industrial forest operators (e.g., Westfraser and Weyerhaeuser).

The final harvest levels of each forest company are approved by the GOA through an annual allowable cut (AAC) (Schreiber and Thomas, 2017). The fundamental components of an AAC determination includes the quantity of available land, the age class distribution of the forest, the yield information, and the constraints associated with managing the forests. In order to increase the allowable cut, forest companies have the option to engage in a range of silvicultural activities, such as using improved seeds (IS) for reforestation to increase yield. The change in AAC due to the silvicultural activities is called the allowable cut effect (ACE). The ACE allows for an immediate increase in the annual harvest by the same amount each year, for the number of years in the forest rotation with an expectation of improvement in growth, regardless of when its direct effect will be realized (Pearse, 1990). ACE would result in an accelerated harvest of old growth forest growing stock and the magnitude of the ACE depends on the amount of old growth forest that is available for immediate harvesting (Hegan and Luckert, 2000). In Alberta, it is the responsibility of the forest industry tenure holders to propose and prove to the government technically sound and credible ways to increase the allowable cut (Weetman, 2002). However, according to Luckert and Haley (1995), the ACE policy has been ineffective in Canada partially due to the uncertainties surrounding the improved yield and the future of tenure arrangements. My analysis first assumes that ACE will be approved by the government with certainty as a “reward” for using improved seeds (IS). I then address the uncertainty of the ACE policy by performing sensitivity analyses regarding the improved yield and adoption rate of IS in section 3.5.2.5.

Similar to the timber supply analysis process in firm level FMPs, I construct a linear programming based timber supply model to character the dynamics of the forest age structures and examine the impact of changing forest growth functions on the provincial level AACs under different scenarios. The dynamics of the forest state are modeled using the Woodstock Forest Modeling System and the Mosek solver. I use a planning horizon of 40 periods, with each period representing five years. Currently in Alberta, timber harvesting decisions are made without considering economic factors (i.e., maximizing total volume instead of maximizing net present value). Therefore, to represent the current practice in Alberta, I maximize the harvest volume for lodgepole pine and white spruce subject to provincial regulatory policies and resource constraints. I present a simple illustrative model on the timber supply simulation process using eqs.(3.1)-(3.4). I assume ϕ represents the set of all species composition strata; ψ represents the set of all planning years; Ω represents the set of the last quarter of the planning horizon.

$$Max\ TV = \sum_{s \in \phi} V_t^s \tag{3.1}$$

subject to

$$\sum_{s \in \phi} V_{t+1}^s - \sum_{s \in \phi} V_t^s \;=\; 0,\ \forall\ t \in \psi \tag{3.2}$$

$$\sum_{s \in \phi} Y_{t+1}^s A_{t+1}^s - \sum_{s \in \phi} Y_t^s A_t^s \;=\; 0,\ \forall\ t \in \Omega \tag{3.3}$$

$$V_t^s = \begin{cases} 0, & \text{if}\ \ Y_t^s < 50 \\ V_t^s, & \text{if}\ \ Y_t^s \geq 50 \end{cases},\ \forall\ t \in \psi, s \in \phi \tag{3.4}$$

where TV is the total volume; V_t^s is the harvest volume of species strata s in year t; Y_t^s is the yield of species strata s in year t; A_t^s is the area of species strata s in year t; $\phi = \{$C-P, C-Sb, C-Sw, CD-P, CD-Sb, CD-Sw, D, DC-P, DC-S$\}$[1]; $\psi = \{1,2,...,200\}$; $\Omega = \{151,152,..., 200\}$. Constraint (3.2) ensures that an even-flow of timber harvest volume is scheduled; constraint (3.3) is consistent with the current forest management planning standard that the amount of operable growing stock must be stable over the last quarter of the planning horizon so that the growing stock is not completely liquidated at the end of the planning horizon (Government of Alberta, 2006); and constraint (3.4) sets the operability limits on the clearcut action so that no development type class with a standing volume of less than

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[1] Each strata is defined as broad cover type-leading species. C=conifer; D=deciduous; CD=conifer and deciduous mixed; DC=deciduous and conifer mixed; Sw=white spruce; Sb=black spruc; P=pine.

50 m^3/ha is harvested (Government of Alberta, 2016).

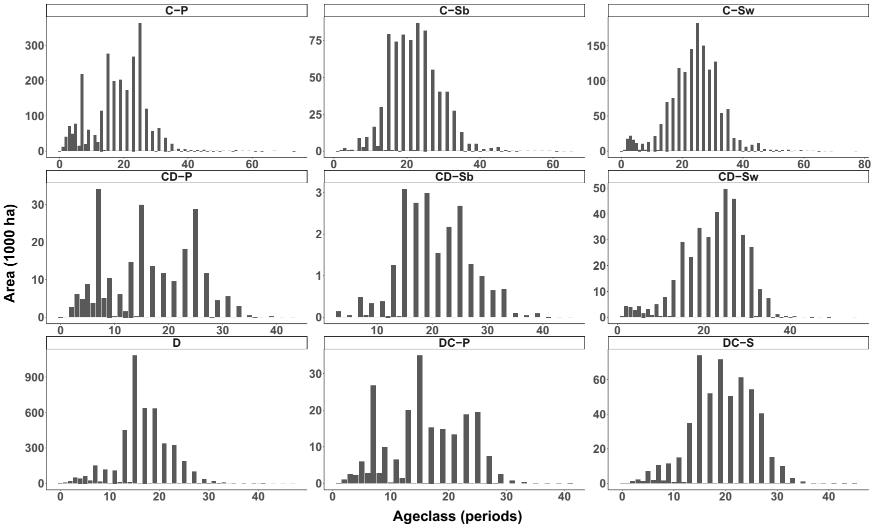

Figure 3.1: Starting age class distributions by species composition strata. Age classes are in five-year wide period. Each strata is defined as broad cover type-leading species. C=conifer; D=deciduous; CD=conifer and deciduous mixed; DC=deciduous and conifer mixed; Sw=white spruce; Sb=black spruce; P=pine. Data source: GOA.

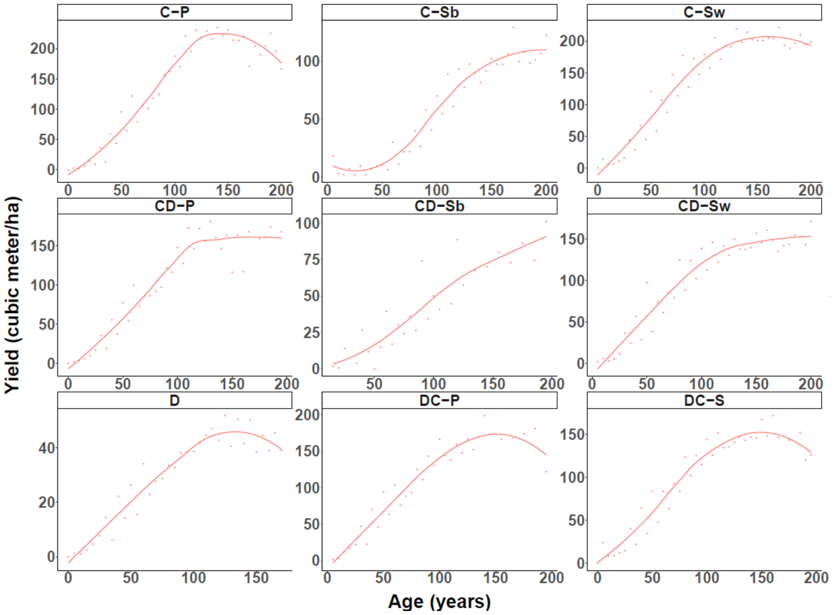

Figure 3.2: Yield curves by species composition strata for initial stands. The definition of strata is the same as Figure 1. Data source: GOA.

Assuming the actual harvest level is the same as the calculated AAC[2], I use forest inventory and growth and yield data from the Government of Alberta as my starting values and calibrate the timber supply model to the AAC level in 2015. I then simulate the annual timber supply under different scenarios. The data was compiled from 20 FMA areas in the province, which covers 95% of the timber production areas in Alberta[3]. Figure 3.1 shows the initial age class distributions of different species composition strata. Since stands regenerated with IS are projected to grow faster than the existing ones, the genetic gain is realized through volume gains. I calculate gains in yields by applying a percent genetic gain to the volume given in the existing provincial yield tables. Figure 3.2 presents the yield curves for existing stands of different species composition strata. All yield curves are based on harvest volumes from clear-cutting. The ACEs attributable to the adoption of IS with a particular level of genetic gain are calculated by repeating the forest level timber supply simulation process under scenarios with and without enhanced growth and yield assumptions. Following Abbott et al. (2009), I assume the lumber recovery rate is fixed over time, indicating that the wood product production will change in parallel with the timber supply change.

3.3.2 Economic Modeling Approach

I identify and measure economic benefits of a forest genomic research project based on an applied welfare analysis. The forest genomic research program is the Resilient Forests (RES-FOR): Climate, Pests & Policy, Genomic Applications project in Alberta[4]. The RES-FOR project only focuses on lodgepole pine (*Pinus contorta var. latifolia*) and white spruce (*Picea glauca*). These two species together account for about 90% of Alberta's merchantable volume of coniferous growing stock, and these species are predominately used for the production of

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[2] Though AACs are higher than actual harvesting levels since about 2005 due to the approval of increased coniferous AACs to deal with the Mountain Pine Beetle (MPB) threat (Government of Alberta, 2017), timber supply is expected to reduce in Alberta due to MPB surge cuts ending and land-base reductions (Schreiber and Thomas, 2017). The actual harvesting level and AACs are expected to be close in the near future.

[3] There were over 550,000 ha in the net landbase which could not be directly assigned to a species composition stratum. These primarily represent harvest areas in the first few age classes. Due to the vintage of the Alberta Vegetation Inventory (AVI) in relation to the time of harvest species composition, AVI were not yet available for these hectares (pers. comm. Nov. 17, 2017, Darren Aitkin, Manager Forest Biometrics Group, Government of Alberta).

[4] The purpose of the RES-FOR project is to integrate phenotyping and genotyping capabilities to enable early identification and incorporation of more desirable and adaptive traits into future forest breeding stock.

SWL (Alberta Agriculture and Forestry, 2017). Therefore, it is appropriate to only consider the SWL industry for the economic evaluation of the RES-FOR research program. Since SWL is a commonly traded commodity, I construct a global trade model (i.e., spatial equilibrium model) to evaluate the economic effect of SWL supply shifts in Alberta. This approach allows for a more detailed representation of markets and requires less restrictive assumptions (Paris et al., 2011).

Samuelson (1952) first described a spatial price equilibrium model as a linear programming problem, and then Takayama and Judge (1971) extended the study by converting the Samuelson formulation into a quadratic programming problem. To illustrate the model, I use a simple two-region trade model as shown in Figure 3.3. Trade will occur since equilibrium prices differ in the two regions. If the sum of a region's domestic price (P^A) and transportation cost is lower than the other region's domestic price (P^B), the two regions will engage in trade until a worldwide equilibrium price (P*) is achieved. The region which cannot clear its supply domestically becomes a net exporter and the region which cannot clear its demand domestically becomes a net importer. The excess supply (ES) function is derived from the exporter's domestic market by subtracting the demand curve from the supply curve at every price greater than the no-trade equilibrium in the domestic market; similarly, the excess demand (ED) curve is derived from the importer's domestic market by subtracting the supply curve from the demand curve at every price less than equilibrium in the domestic market. The net social welfare is derived by maximizing the sum of the area under the excess demand curves less the sum of the area under the excess supply curves plus transportation costs.

3.3.2.1 Countries and (or) Regions

Assuming interconnected competitive markets, the model considers two net demand regions and four net supply regions. In 2015, BC accounted for 63.4% of the total SWL export in Canada and 25.6% of the total SWL export in the world (Food and Agriculture Organization, 2015). Alberta is the focus area in this study. Thus, Canada is divided into three regions: Alberta (AB), British Columbia (BC) and the rest of Canada (ROC). The remaining export

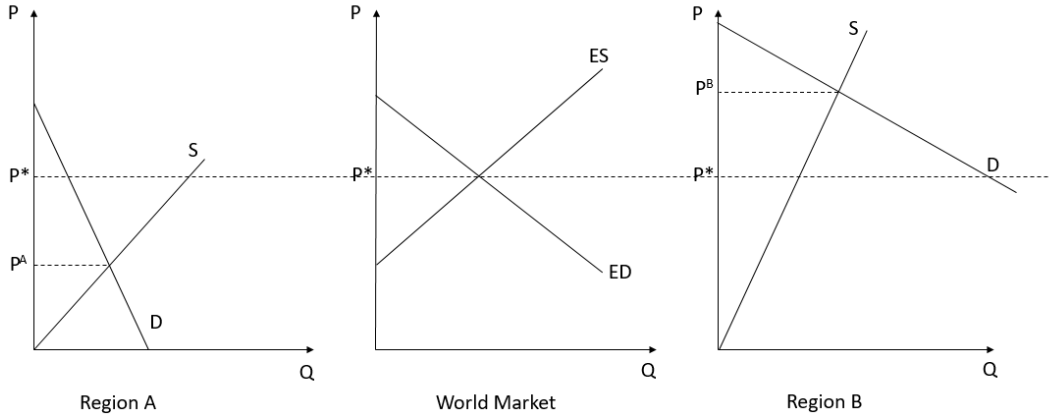

Figure 3.3: Two-region trade model

regions are grouped together as rest of the world export (ROW_ex).

The demand for SWL is dominated by the U.S. where almost 31.6% of all foreign exports were destined in 2015 (FAO, 2015). In 2015, 94% of the total U.S. SWL imports were from Canada. Figure 3.4 shows the major SWL markets of AB. It is obvious that the U.S. is the single most important trade partner for AB with 96% of total AB's SWL exports being shipped to the U.S.. Thus, the U.S. is treated as an import region in this study. The remaining import regions are grouped together as rest of the world import (ROW_im).

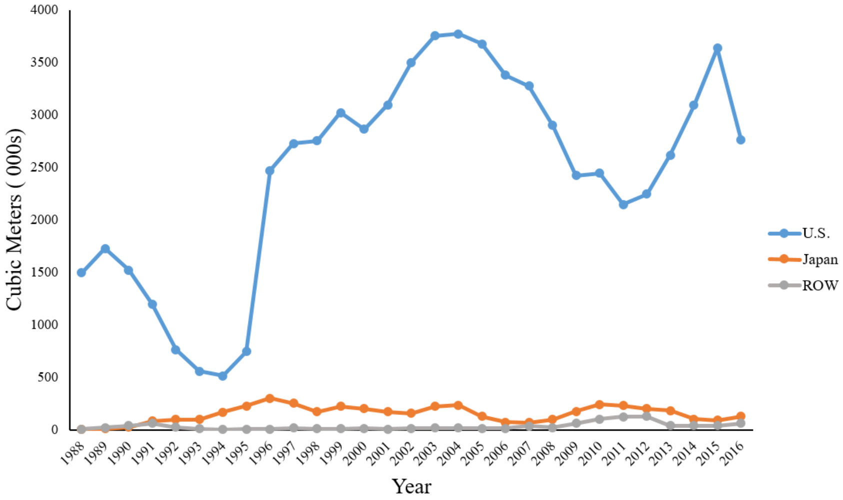

Figure 3.4: Alberta SWL exports to major markets, 1988-2016. ROW refers to rest of the world. Data source: Canadian International Merchandise Trade Database.

3.3.2.2 Derivation of Net Demand and Supply Estimation

The model considers n net demand regions and m net supply regions. Both supply and demand functions are assumed to be linear and therefore have constant slope[5]. According to Delcourt (1995), linear demand and supply are easily integrated and are robust in determining an equilibrium. In the demand function, factors that could affect the lumber consumption, such as the housing market, interest rates, income growth, population and technology, are not explicitly included, but included as an intercept shifter. Similar to the demand function, the lumber supply function is also defined as the relationship between the quantity produced and the price. Investment in enhanced silviculture, technical change and government policy can all cause changes in future lumber supply. These factors are also included as intercept shifters in the model. To reduce model complexity, cross-effects between products were not considered in this study.

Suppose the net demand region i (i=1, . . . , n) and the net supply region j (j=1, ..., m) of SWL have the following linear domestic demand and supply functions:

$$q_i^d = a_i + b_i \rho_i^d \tag{3.5}$$

$$q_i^s = c_i + d_i \phi_i^s \tag{3.6}$$

$$q_j^d = a_j + b_j \rho_j^d \tag{3.7}$$

$$q_j^s = c_j + d_j \phi_j^s \tag{3.8}$$

where a_i, b_i and a_j, b_j are the intercepts and slopes of the domestic demand function in regions i and j, respectively; c_i, d_i and c_j, d_j are the intercepts and slopes of the domestic supply function in regions i and j, respectively; q_i^d, q_i^s and q_j^d, q_j^s represent the domestic consumption and production in regions i and j, respectively; and ρ_i^d, ϕ_i^s and ρ_j^d, ϕ_j^s represent the domestic demand and supply prices in regions i and j, respectively.

The intercepts and slopes of eq.(3.5)-(3.8) can be calculated based on the base-year data of production, consumption, mean market prices, and the own-price elasticities of domestic supply and demand for SWL, which are expressed as follows:

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[5] A change in slope may pose a problem in solving for equilibrium values (Chang and Gaston, 2014).

$$b_i = e_i^d \left(\frac{q_i^d}{p_i^d} \right) \tag{3.9}$$

$$a_i = q_i^d - b_i \rho_i^d \tag{3.10}$$

$$d_i = e_i^s \left(\frac{q_i^s}{\phi_i^s} \right) \tag{3.11}$$

$$c_i = q_i^s - d_i \phi_i^s \tag{3.12}$$

$$b_j = e_j^d \left(\frac{q_j^d}{p_j^d} \right) \tag{3.13}$$

$$a_j = q_j^d - b_j \rho_j^d \tag{3.14}$$

$$d_j = e_j^s \left(\frac{q_j^s}{\phi_j^s} \right) \tag{3.15}$$

$$c_j = q_j^s - d_j \phi_j^s \tag{3.16}$$

where e_i^d, e_i^s and e_j^d, e_j^s represent the own-price elasticities of domestic demand and supply of SWL in regions i and j, respectively. To derive the net demand and supply functions, net demand and supply elasticities are required and can be calculated as follows:

$$\varepsilon_i^d = e_i^d \left(\frac{q_i^d}{M_i} \right) - e_i^s \left(\frac{q_i^s}{M_i} \right) \tag{3.17}$$

$$\varepsilon_j^s = e_j^s \left(\frac{q_j^s}{X_j} \right) - e_j^d \left(\frac{q_j^d}{X_j} \right) \tag{3.18}$$

where ε_i^d is the net demand elasticity in region i and ε_j^s is the net supply elasticity in region j. M_i is the import quantity of SWL in region i, and X_j is the export quantity of SWL in region j. The intercepts and slopes of the net demand and net supply functions can be derived as follows:

$$\alpha_i = \frac{(c_i - a_i)}{(b_i - d_i)} \tag{3.19}$$

$$\beta_i = \frac{1}{\left[\varepsilon_i^d \left(\frac{M_i}{\rho_i^d}\right)\right]} \tag{3.20}$$

$$\gamma_j = \frac{(c_j - a_j)}{(b_j - d_j)} \tag{3.21}$$

$$\delta_j = \frac{1}{\left[\varepsilon_j^d \left(\frac{X_j}{\phi_j^s}\right)\right]} \tag{3.22}$$

I assume that changes in consumption and production for each time period can be measured by changing the intercepts of domestic demand and supply functions. Specifically, the intercepts of domestic demand and supply functions are defined as below:

$$a_{i(t+1)} = a_{it} + q_{it}^d(R_i^D)[(t+1) - t] \tag{3.23}$$

$$c_{i(t+1)} = c_{it} + q_{it}^s(R_i^S)[(t+1) - t] \tag{3.24}$$

$$a_{j(t+1)} = a_{jt} + q_{jt}^d(R_j^D)[(t+1) - t] \tag{3.25}$$

$$c_{j(t+1)} = c_{jt} + q_{jt}^s(R_j^S)[(t+1) - t] \tag{3.26}$$

where $t+1$ is the year of the next period and t is the year of the current period. R_i^D and R_j^D are the expected annual SWL demand changes (%) in regions i and j, respectively. R_i^S and R_j^S are the expected annual SWL supply changes (%) in regions i and j, respectively. Since the intercept parameters of the domestic demand and supply functions were updated for each year, the intercept parameters of the net demand and supply functions in the model are also changed accordingly.

3.3.2.3 Positive Mathematical Programming

Samuelson (1952) and Takayama and Judge (1971) have shown that the optimal trade flow could be determined using the mathematical programming model. The specification of a spatial trade model among regions corresponds to the maximization of a quasi-welfare function

(QWF) subject to constraints regarding the demand and the supply of the various regions. The QWF objective function is defined as the sum of all regional demand integrals less the sum of all regional supply integrals and interregional transportation costs (eq. 3.27), which corresponds to the maximization of the sum of consumer and producer surpluses netted out of total transaction costs (Samuelson, 1952; Takayama and Judge, 1971).

$$Max \sum_{i=1}^{n} \int_{0}^{M_i} D_i(M_i)\,\mathrm{d}M_i - \sum_{j=1}^{m} \int_{0}^{X_j} S_j(X_j)\,\mathrm{d}X_j - \sum_{i=1}^{n}\sum_{j=1}^{m} t_{ij}Q_{ij} \tag{3.27}$$

where D_i and S_j are the demand and supply of SWL for the regions; Q_{ij} is the quantity of SWL exported from region j to region i; t_{ij} is the per unit transportation cost of SWL from region j to region i. The transportation costs among different regions are considered to obtain the competitive optimum solution for regional prices and quantities and interregional flows when total economic welfare (trade surplus) of all markets is maximized. To be used in the algorithm of the objective function, the net demand and supply equations are assumed in its inverted form. The inverse demand and supply functions are derived from the domestic demand and supply functions in each region as follows:

$$P_i^d = \alpha_i - \beta_i M_i \ , i = 1, \ldots .n \tag{3.28}$$

$$P_j^s = \gamma_j - \delta_j X_j \ , j = 1, \ldots .m \tag{3.29}$$

where α_i and β_i denote the intercept and slope of the net demand function of SWL, and the variables P_i^d and M_i represent the demand (import) price and total quantity demand (imports) of SWL for region i, respectively. γ_j and δ_j are the intercept and slope of the net supply function of SWL, and the variable P_j^s and X_j denote the supply (export) price and total supply (exports) of SWL for region j. Therefore, the integrals of eq.(3.27) can be expressed in terms of quadratic function in eq.(3.30) along with the related constraints in eqs (3.31)-(3.34):

$$Max \sum_{i=1}^{n}[\alpha_i M_i - \frac{1}{2}\beta_i (M_i)^2] - \sum_{j=1}^{m}[\gamma_j X_j + \frac{1}{2}\delta_j (X_j)^2] - \sum_{i=1}^{n}\sum_{j=1}^{m} t_{ij} Q_{ij} \tag{3.30}$$

subject to

$$\begin{aligned} \sum_{i}^{n} Q_{ij} &\leq X_j && (3.31) \\ \sum_{j=1}^{m} Q_{ij} &\geq M_i && (3.32) \\ M_i, X_j, Q_{ij} &\geq 0 && (3.33) \\ \sum_{i=1}^{n} M_i - \sum_{j=1}^{m} X_j &= 0 && (3.34) \end{aligned}$$

Constraint (3.31) ensures that the SWL supply of region j is greater or equal to the total export of SWL in region j. Constraint (3.32) ensures that the total SWL import of region i is at least as big as what is consumed in region i; constraint (3.33) ensures prices and quantities are positive; and constraint (3.34) ensures that the markets clear.

The standard mathematical model proposed by Samuelson (1952) and Takayama and Judge (1971) is critiqued by Paris et al. (2011) for the discrepancy between the equilibrium solution and the observed demand, supply and level of trade flows. The cause of the discrepancy problem can be attributed to the imprecision of unit transaction cost (Paris et al., 2011). To generate solutions that perfectly reproduce observed supply and demand quantities as well as prices and trade flows for a given base year, I adopt the calibration method proposed by Paris et al. (2011), which is an extension of the positive mathematical programming method (Howitt, 1995). Specifically, the unit transaction costs are further adjusted by either adding or subtracting the shadow price from the level of the given costs (Paris et al., 2011).

Following Paris et al. (2011), van Kooten and Johnston (2014) and Chang and Gaston (2014), the calibration process is implemented in three steps. First, the objective function (eq.3.27) is solved, subject to all the constraints (eqs.3.31-3.34) and an additional calibration constraint (eq.3.35).

$$Q_{ij} = Q'_{ij} \tag{3.35}$$

where Q'_{ij} represents the observed trade flow of lumber between export region j and import region i. After solving the model, the dual (shadow) prices λ_{ij} were generated. Second, the shadow prices generated in the first step were used to adjust the original transportation costs in the objective function to achieve the “effective” transaction costs between export and import regions. The new objective function is shown as follows:

$$Max \sum_{i=1}^{n} \int_{0}^{M_i} D_i(M_i)\, \mathrm{d}M_i - \sum_{j=1}^{m} \int_{0}^{X_j} S_j(X_j)\, \mathrm{d}X_j - \sum_{i=1}^{n} \sum_{j=1}^{m} (t_{ij} + \lambda_{ij}) Q_{ij} \tag{3.36}$$

Finally, the modified objective function (eq.3.36) was solved again subject to the original constraints (eqs.3.31-3.34) in order to calibrate the spatial equilibrium model perfectly to the observed trade flows, quantities of production and consumption and prices. The model is solved by using the Microsoft Excel software package called What’s Best!. It allows users to try different trade scenarios, perform sensitivity analyses or impose additional constraints with little difficulty (Chang and Gaston, 2014).

To define the initial equilibrium of the model, values are assigned for all elasticities as well as initial prices and quantities shown in eqs(3.9)-(3.16). Table 3.1 reports the regional SWL production, consumption, mean price values and elasticity estimates. Table 3.2 reports the trade flow data between regions. The base-year prices of SWL in each region are derived from the weighted means of the unit values of exports or imports (Chang and Gaston, 2014). I use positive mathematical programming to calibrate the spatial equilibrium model to actual SWL trade flows among regions so that the transportation costs represent the shadow price which consider factors that are not included in the transportation cost (e.g., heterogeneous lumber quality, tariffs, etc). The results of the calibrated transportation costs (shadow prices) for this study are shown in Table 3.3.

Table 3.1: Regional softwood lumber production, consumption, prices and demand and supply elasticities in base year 2015 used to define the initial equilibrium.

Region	Production (million m^3)	Consumption (million m^3)	Mean price (CAD\$ m^{-3})	Demand elasticity	Supply elasticity
Net supply regions					
AB	9.27	5.50	171	-0.34	1
BC	31.18	4.98	221	-0.34	1
ROC	22.53	11.14	181	-0.34	1
ROW_ex[a]	101.55	40.51	350	-0.34	1
Net demand regions					
U.S.	54.34	86.70	204	-0.34	1
ROW_im	164.71	234.74	332	-0.34	1

† The source used for elasticity estimates is from Cardellichio (1989) for all regions. All other information in the table was estimated by the author using data from FAO (2015), CANSIM table 303 0064 (Statistics Canada, 2015), and National Forest Database (2015). [a] Including Austria, Chile, Finland, Latvia, New Zealand, Romania, Russian Federation, Sweden, Belarus, Brazil, and Ukraine.

Table 3.2: Product group trade flows in base year 2015 (million m^3).

	Import region		
Export Region	U.S.	ROW_im	Total
AB	3.64	0.13	3.77
BC	15.53	10.67	26.20
ROC	11.27	0.12	11.38
ROW_ex	1.93	59.11	61.04
Total	32.36	70.03	102.39

† The trade flows in the table were estimated by the author using data from the Canadian International Merchandise trade database (2015), and UN Comtrade database (2015).

Table 3.3: Adjustments (shadow prices) to the transportation cost (CAD$ m^{-3})

	Import region	
Export Region	U.S.	ROW_im
AB	33	161
BC	-17	111
ROC	23	151
ROW_ex	-146	-18

† Note: Adjustment (shadow price) were used to calibrate the model to the observed trade flow.

3.3.2.4 Dynamics

A tree genetic improvement program will entail a sequence of steps leading to improvements in genetic gain over time. Thus, it is important to identify the timing of a supply shock and the timing of the shock's effect. Although the change in supply that occurs in a certain year is assumed to be sustained at a constant level throughout time, the effect of the shock varies over time as the market is able to adjust to the change throughout time. This study estimates the economic effects over a 38-year period from 2016 to 2053.

3.3.2.5 Net Present Value of Economic Benefits

To arrive at a cumulative estimate of the value of the research program today, I calculate the discounted net economic benefit for the entire stream of research gains (NPV^{NEB}), which is the discounted sum of producer and consumer surpluses net of R&D expenditures from 2016 to 2053 (eq.3.37).

$$NPV^{NEB} = \sum_{t=0}^{T}(PV_t^{CS} + PV_t^{PS} - PV_t^{E}) \tag{3.37}$$

where NPV^{NEB} is the net present value of the economic benefits of the research program; ρ is the discount rate; PV_t^{CS} is the present value of consumer surplus in year t; PV_t^{PS} is the present value of producer surplus in year t; PV_t^{E} is the present value of R&D cost in year t.

3.4 Simulation Scenarios

I first construct a plausible baseline scenario of what would have happened to the benefits in question if the research being evaluated is not being performed. I then conduct simulations under a range of assumptions about scenarios regarding potential use of the genomics tools to increase timber supply. Under each alternative scenario, producer and consumer benefits are computed for each year of the simulation as the change in producer surplus and consumer surplus, relative to the baseline scenario. Annual total benefits are equal to the sum of producer and consumer benefits.

3.4.1 Business As Usual

The business as usual (BAU) scenario represents economic outcomes given the existing improved regeneration materials. The model's ability to analyze alternative scenarios allows for the examination of a variety of different future conditions affecting domestic supply and demand conditions (Delcourt, 1995). To project the future supply and demand of SWL, I exogenously shift intercepts of domestic supply and demand curves in each region. Assumptions about the annual changes in demand and supply curves are made based on the historical mean annual change (%) and expected mean annual (%) change in the future.

Figure 3.5 shows the historical SWL production in all regions from 2005 to 2016. The historical mean annual change is negative in BC (-2%), ROC (-1%), and U.S.(-1%), but positive in AB (2%), ROW_ex (1%) and ROW_im (1%). For ROC, ROW_ex and ROW_im, I assume that the annual changes will follow the historical trends for the period 2016-2035. For AB, annual allowable cut has increased in recent years due to the new management strategies in regards to the Mountain Pine Beetle (MPB) infestation. However, in the near future, timber supply is expected to decline back to the pre-MPB infestation level as a result of MPB surge cuts ending and land-base reductions (Schreiber and Thomas, 2017). This indicates a 25% reduction in timber supply. Thus, I assume that SWL supply in AB will decrease by 25% from 2021 to 2035. For BC, according to the Forest Analysis & Inventory Branch of the Ministry of Forests, a drop in timber supply of 25% is also expected over the next 20 years due to MPB infestation, dropping from 76.71 million cubic metres in 2016 to 56.91 cubic metres in 2035. Thus, the annual reduction in supply for BC is assumed to be 1.25% from 2016-2035. For the U.S., though historically the mean annual production is -1%, U.S. SWL production is expected to increase in the future due to the U.S. export duties imposed on Canadian lumber in 2017 and the increase of plantation forests in the southern U.S. (Chang and Gaston, 2014). Therefore, I assume the mean annual change in the U.S. SWL production is 0%.

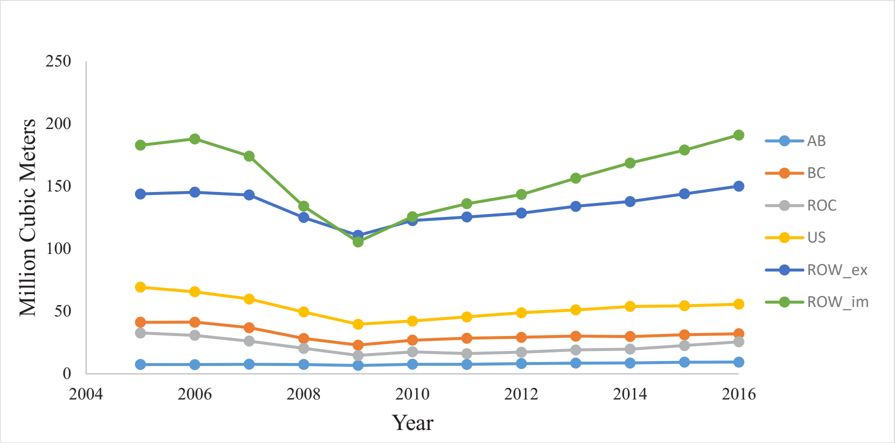

Figure 3.5: Historical softwood lumber production by regions, 2005-2016.

Following Chang and Gaston (2014), I assume that there is no change in SWL demand in Canada over time. The annual increase in SWL demand for the rest of the world import (ROW_im) and export regions (ROW_ex) is assumed to be 1.5% due to population increase and economic growth. In the U.S., the annual increase in demand of SWL is assumed to be 3% due to the growing U.S. demand in housing. Since it is very difficult to predict the SWL supply and demand for the period of 2036-2053, I assume the demand and supply are constant since 2036 under the BAU scenario[6]. I summarize assumptions about future mean annual supply and demand changes (%) in SWL products for all regions under the BAU scenario in Table 3.4.

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[6] Since I am interested in the change of welfare between BAU and other genomic scenarios instead of projecting future production and consumption, this approach should be legitimate and it allows us to estimate the effect of supply disturbances caused by genomic technology in isolation.

Table 3.4: Assumptions for future mean annual supply and demand changes (%) for softwood lumber in both import and export regions.

	2016-2020		2021-2035		2036-2053	
	Demand	Supply	Demand	Supply	Demand	Supply
Export Regions						
AB	0	0	0	-1.6	0	0
BC	0	-1.25	0	-1.25	0	0
ROC	0	-1	0	-1	0	0
ROW_ex	1.5	1	1.5	1	0	0
Import Regions						
U.S.	3	0	3	0	0	0
ROW_im	1.5	1	1.5	1	0	0

† The assumptions are based on reported data from FAO (2009), the British Columbia Ministry of Forests and Range (2007), and Chang and Gaston (2014).

3.4.2 Breeding Strategies

Traditional tree improvement programs consist of repeated cycles, each with distinctive breeding, testing and selection phases (Namkoong et al., 1988). At the completion of each cycle, breeders identify superior individuals which are then used in subsequent breeding cycles and elite genotypes are used to develop seed orchards for abundant production of genetically improved seeds (IS) for reforestation (White et al., 2007). According to El-Kassaby et al. (2012), the traditional breeding process is resource-demanding and long-term in nature and the pedigreed offspring and subsequent testing phases are a major resource drain with time bottlenecks. The current genomics-assisted tree breeding (GATB) research is being undertaken to generate advanced genomic selection techniques that can significantly reduce breeding cycle times and increase selection accuracy allowing for more rapid genetic gain. For the purposes of this study, genetic gain at a rotation age is defined as predicted increase in volume for selected trees over wild trees. Thus, the technology is "yield-enhancing".

I conduct simulations of the impacts of alternative breeding techniques (i.e., TB and GATB), characterized by alternative combinations of assumptions about genetic gains, R&D

lags and adoption rates. Since genomics research is still developing and the exact effects of the new technology on the timber growth and potential lags in commercialization are unknown, I interviewed the scientists conducting the research to better understand the research being conducted and its potential future outcomes. Based on expert opinion, I develop potential pathways of producing 2nd and 3nd generation IS to achieve higher growth gain using both TB and GATB (Appendix A & B). Specifically, in the scenario of producing 2nd generation IS, both TB and GATB are associated with the same R&D lags of 18 years (Appendix A). However, as previous studies have demonstrated that GATB can provide more accurate genetic variance components and breeding value estimates than TB (El-Kassaby et al., 2012; EI-Dien et al., 2016), GATB has higher selection accuracy and allows for a higher level of genetic volume gain. Thus, this scenario examines the higher selection accuracy effect only. In the scenario of producing 3rd generation IS, compared with TB, GATB can not only achieve higher genetic volume gain, it can also shorten the breeding cycle by 16 years (Appendix B). Therefore, this scenario examines the combined effect of higher selection accuracy and a shorter breeding cycle. For both scenarios, I assume that the adoption rate is 100% once the IS are available and the technology will have 100% efficacy in yield-enhancement. I summarize the level of genetic volume gain, R&D lags and R&D costs[7] in Table 3.5.

Table 3.5: Elicited parameters for different R&D scenarios.

Breeding Strategies	Genetic Volume Gain (%)	R&D Lags (years)	R&D Costs (M C$)
2nd Generation IS			
TB	15	18	6.5
GATB	20	18	16.4
3rd Generation IS			
TB	25	38	7.9
GATB	30	22	16.3

† The assumptions are based on expert opinions. TB refers to traditional breeding; GATB refers to genomics-assisted tree breeding; IS refers to improved seeds. See Appendix A & B for the specific R&D process for each scenario.

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[7] See Appendix C for detailed R&D cost information.

3.5 Results

In this section, I first present the timber supply simulation results. I then report the economic simulation results which include results of model calibration, model validation, welfare distribution and sensitivity analyses.

3.5.1 Timber Supply Simulation

Table 3.6 reports the simulated ACEs for all scenarios. The baseline represents the calibrated AAC level in 2015. Since the currently available improved seeds (IS) have on average a 5% genetic volume gain at rotation, I assume all forest companies in Alberta adopt the current available IS since 2018 in the BAU scenario[8].

Table 3.6: Simulated annual allowable cuts (AACs) and allowable cut effects (ACEs) for all scenarios, relative to the baseline.

Scenarios	AAC(M m^3)	ACE(M m^3)	Timber supply change (%)	SWL supply change (%)
Baseline	18.5	0	0.00	0.00
BAU	19.2	0.7	3.8	3.8
2nd Gen. Improved Seeds				
TB	20.7	2.2	11.9	11.9
GATB	21.3	2.8	15.1	15.1
3rd Gen. Improved Seeds				
TB	22.6	4.1	22.2	22.2
GATB	23.3	4.8	25.9	25.9

† Note: Gen. represents generation; TB represents traditional tree breeding; SWL represents softwood lumber; GATB represents genomics-assisted tree breeding; BAU represents business as usual.

As shown in Table 3.6, all ACEs are positive as mature reserves are available for immediate AAC increases. As expected, the ACE increases as the level of genetic gain increases.

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[8] In 2015, very few improved seeds were used in Alberta. A new directive in Alberta requires that where artificial reforestation activities are approved to occur, timber disposition holders must use improved seeds made available for sale from approved Controlled Parentage Program seed orchards and 2018 is the first planting season affected by the directive (Alberta Agriculture and Forestry, 2016). Thus, I assume currently available IS with 5% genetic volume gain will be adopted by all forest companies since 2018 in the BAU scenario.

Since I assume a fixed lumber recovery factor over time, SWL supply has the same percentage change as timber supply. In the BAU scenario, the ACE causes 3.8% increase in SWL supply in 2018. In the scenario of producing 2nd generation IS, the ACE causes 11.9% increase in SWL supply in 2033 when TB is adopted and 15.1% increase in SWL supply in 2033 when GATB is adopted. In the scenario of producing 3rd generation IS, the ACE causes 22.2% increase in SWL supply in 2053 when TB is adopted and 25.9% increase in SWL supply in 2037 when GATB is adopted. The calculated SWL supply changes in Table 3.6 serve as inputs to shift the SWL supply curves in the economic model.

3.5.2 Economic Simulation

Table 3.7 presents calibrated SWL production, consumption, trade and prices for the spatial equilibrium model in the base year of 2015.

Table 3.7: Calibrated SWL production, consumption, trade, and prices for the trade model and comparisons with the actual levels in base year 2015.

	Production		Consumption		Trade		Price	
Region	Million (m^3)	% of actual level	Million (m^3)	% of actual level	Million (m^3)	% of actual level	CAD\$ (m^{-3})	% of actual level
Export								
AB	9.27	100	5.50	100	3.77	100	171	100
BC	31.18	100	4.98	100	26.20	100	221	100
ROW	22.53	100	11.14	100	11.38	100	181	100
ROW_ex	101.55	100	40.51	100	61.04	100	350	100
Import								
U.S.	54.33	100	86.70	100	32.36	100	204	100
ROW_im	164.71	100	234.74	100	70.03	100	332	100

† Note: Adjustment (shadow price) were used to calibrate the model to the observed trade flows.

The production, consumption, trade and price levels of 2015 are precisely duplicated using positive mathematical programming (Table 3.7), and therefore, they provide a good foundation for projecting global SWL market conditions during the 2016-2053 period. In each scenario defined in terms of a particular set of assumptions about the R&D lag and genetic gain of IS, I simulate region-specific production, consumption, price and trade of SWL over a 38-year horizon. The BAU scenario reflects currently available technology (i.e., currently available IS). I then repeat these simulations allowing for the adoption of genomic technology. Comparing the outcomes between the simulation for a particular scenario versus the BAU with current technology yields a measure of the effect of the introduction of the new technology. I calculate changes in producer and consumer surplus as a result of the adoption of different IS for all scenarios.

3.5.2.1 Model Validation

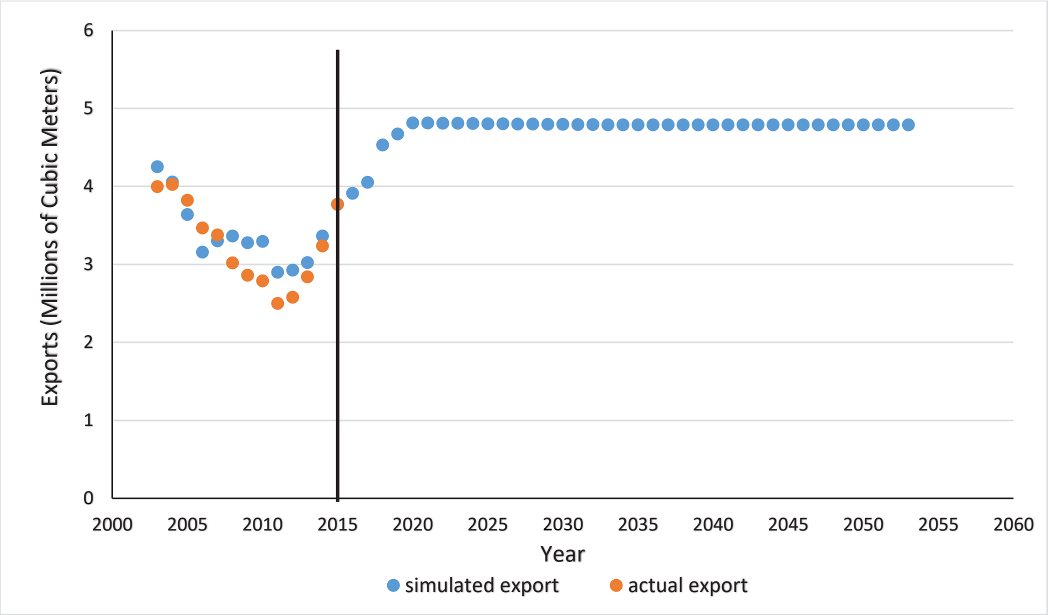

Figure 3.6: Simulated and historical SWL exports in Alberta. Mean square error =8.3%.

I check the validity of the model and its ability to predict SWL market behavior over 38 years by comparing the simulated historical SWL exports against the real historical SWL exports in Alberta. I first collect historical data on SWL production, consumption, exports and imports of all regions for the period of 2003-2016. I then calculate the annual changes of SWL supply and demand in all regions based on the real historical data. Lastly, the calculated annual changes are used to shift the demand and supply curves of the calibrated spatial equilibrium model and to derive simulated historical production, consumption, exports, and imports quantities. Figure 3.6 presents real historical and model-predicted historical and future values of SWL exports in Alberta that are developed in the process described above using baseline parameter values.

3.5.2.2 Gross and net economic benefits from adopting TB and GATB

Figure 3.7 shows the net returns from adopting different breeding strategies to Alberta after accounting for R&D costs. These returns include benefits received by producers and consumers. My estimates suggest that all breeding strategies are likely to generate positive benefits. In both cases, the economic returns associated with GATB are higher than the economic returns associated with TB, indicating that the use of genomic technology can generate greater gains. Specifically, if the goal is to produce the 2nd generation IS, GATB research has the potential to generate an additional C$404.5 million than TB; if the goal is to produce the 3rd generation IS, GATB research has the potential to generate an additional C$ 2044.6 million over TB. The additional benefits in the first case (2nd generation IS) is lower because there is only a higher selection accuracy effect where the 2nd generation IS produced using GATB has higher genetic gain than the 2nd generation IS produced using TB, and the R&D lags are the same for TB and GATB (18 years). The additional benefits in the second case (3rd generation IS) is significantly higher because there is not only a higher selection accuracy effect but also a 16-year R&D time-saving associated with GATB. Therefore, the main driving factor of the additional benefit is the time saved during the breeding process instead of the higher selection accuracy effect in this case. While the 2nd generation IS produced using TB has lower genetic gain than the 3rd generation IS created using TB (15% < 25%), the net returns from the 2nd generation TB research is significantly higher than the returns from the 3rd generation TB research (1B > 0.1B). This is because it takes an additional 20 years to develop the 3rd generation IS and the economic returns are highly discounted over time. This reinforces the importance of a shorter breeding cycle.

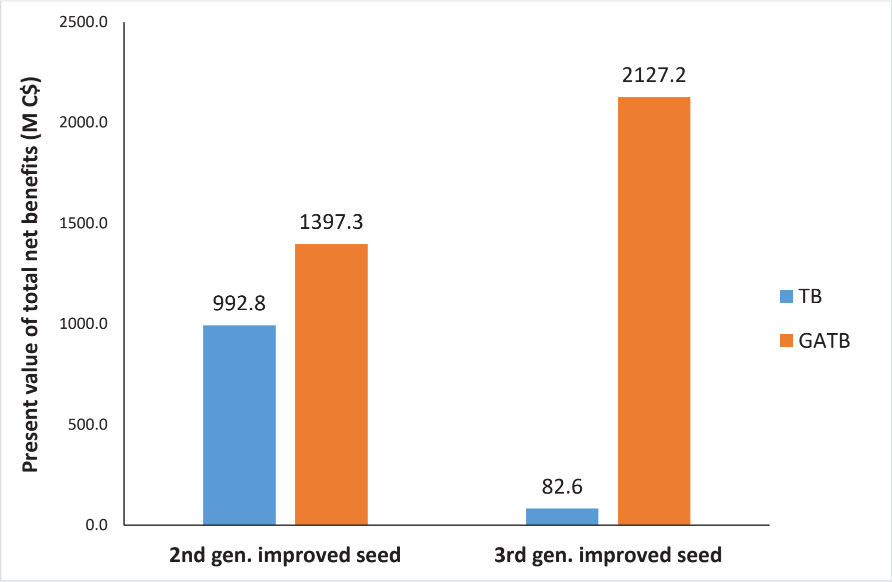

Figure 3.7: Present value of total net benefit in Alberta from 2016 to 2053, r=4%. TB refers to traditional breeding. GATB refers to genomics-assisted tree breeding. Gen. refers to generation.

3.5.2.3 Welfare effects of using TB and GATB to produce 2nd generation improved seed

Table 3.8(a) presents the average annual changes in consumer surplus, producer surplus, and total benefits of using 2nd generation IS for reforestation, compared with the BAU scenario. The measures of changes in economic surplus are expressed as annual averages of undiscounted changes over a 38-year horizon in constant 2015 dollar values. I summarize the counterpart discounted present value measures in Table 3.8(b), computed using a real discount rate of 4% per annum. In the following discussion, unless stated otherwise, I refer to the average annual values of the undiscounted measures of changes in economic surplus.

In most of the regions, the annual change in producer surplus is negative, representing a net loss. However, in the technology adoption region-Alberta, the new technology yields a benefit to producers. This is because the SWL supply increase in Alberta brings the equilibrium price down and regions without yield gains from the technology are therefore worse off. Across all regions, the annual change in consumer surplus is positive. Thus, all consumers of SWL experience net gains when supply increases and price decreases. The net benefit is the sum of producer and consumer surplus, which is positive for AB, the U.S. and

Table 3.8: Benefits from using 2nd generation improved seeds, relative to BAU scenario (Millions of C$).

	TB			GATB		
	Changes in PS	Changes in CS	Total benefit	Changes in PS	Changes in CS	Total benefit
(a) Annual Average Undiscounted Benefits, 2016-2053						
AB	75.54	1.13	76.68	106.88	1.58	108.46
BC	-6.69	1.05	-5.64	-9.34	1.47	-7.87
ROC	-5.31	2.31	-3.00	-7.41	3.22	-4.18
ROW_ex	-30.37	11.49	-18.89	-42.37	16.03	-26.34
U.S.	-14.92	29.82	14.91	-20.80	41.61	20.81
ROW_im	-52.66	66.45	13.79	-73.45	92.71	19.25
(b) Annual Average Discounted Benefits, 2016-2053						
AB	25.91	0.39	26.30	36.66	0.54	37.20
BC	-2.30	0.36	-1.94	-3.20	0.50	-2.70
ROC	-1.82	0.79	-1.03	-2.54	1.11	-1.43
ROW_ex	-10.41	3.94	-6.47	-14.52	5.49	-9.03
U.S.	-5.11	10.22	5.11	-7.13	14.26	7.13
ROW_im	-18.04	22.78	4.73	-25.17	31.78	6.61

† Note: The total benefit is the sum of changes in consumer and producer surplus. "PS" refers to producer surplus and "CS" refers to consumer surplus. All values in Panel a and b are expressed in real 2015 dollars. Values in Panel b are discounted to 2015 present values using a real discount rate of 4 % per annum.

ROW_im, but negative for BC, the ROC and ROW_ex. In the case the import region (U.S. and ROW_im), producer surplus losses are outweighed by consumer surplus gains. However, in other regions where producers also experience a loss (BC, ROC, ROW_ex), the gain in consumer surplus cannot compensate for the loss in producer surplus, resulting in a net loss in those regions. In Alberta, the adoption of GATB yields significantly higher economic benefits than the use of TB. With TB, the net benefit is projected to be $76.68 million which is smaller than the economic benefits yielded by GATB ($108.46 million).

Though many of the regions experience a loss in producer surplus, the impacts are negligible in relative terms. Table 3.9(a) presents the projected mean annual percentage changes in production, consumption, trade, price and welfare in all regions when TB is adopted while Table 3.9(b) shows the counterpart measures when GATB is adopted. It is obvious that with the exception of the significant impacts on Alberta, the adoption of genomic technology in Alberta plays a minor role in global SWL markets. The mean annual impacts on production, consumption, trade, price, consumer surplus, producer surplus and total surplus are less than 0.4% in all regions except Alberta. This is because Alberta only produces about 2% of the world's SWL, and therefore, the increased supply of Alberta SWL will only affect the price marginally over time. Based on the same reasoning, the gain in producer surplus is significantly larger than the gain in consumer surplus in Alberta. Thus, in a competitive SWL market, Alberta producers can act almost as price takers and enjoy benefits from the increasing timber supply and SWL production.

Table 3.9: Projected mean annual changes (%) in production, consumption, trade quantities, prices and welfare, relative to BAU scenario.

Region	Production	Consumption	Trade	Price	Consumer Surplus	Producer Surplus	Total Surplus
(a) TB with an 18-year R&D lag and 15% genetic gain, 2016-2053							
AB	2.83	0.03	5.78	-0.07	0.07	5.75	2.53
BC	-0.07	0.03	-0.09	-0.06	0.05	-0.15	-0.09
ROC	-0.08	0.03	-0.17	-0.07	0.06	-0.17	-0.04
ROW_ex	-0.03	0.01	-0.06	-0.04	0.02	-0.07	-0.02
U.S.	-0.06	0.02	0.11	-0.06	0.04	-0.13	0.02
ROW_im	-0.03	0.01	0.19	-0.04	0.03	-0.07	0.00
(b) GATB with an 18-year R&D lag and 20% genetic gain, 2016-2053							
AB	5.73	0.07	11.66	-0.15	0.14	12.05	5.32
BC	-0.15	0.05	-0.19	-0.12	0.10	-0.30	-0.17
ROC	-0.17	0.06	-0.34	-0.14	0.13	-0.33	-0.09
ROW_ex	-0.07	0.02	-0.12	-0.08	0.05	-0.14	-0.04
U.S.	-0.13	0.03	0.20	-0.13	0.07	-0.25	0.03
ROW_im	-0.07	0.03	0.38	-0.08	0.05	-0.13	0.01

3.5.2.4 Welfare effects of using TB and GATB to produce 3rd generation improved seed

Table 3.10 shows the undiscounted (a) and discounted (b) annual average economic benefits of using the 3rd generation IS produced by TB and GATB for reforestation.

Table 3.10: Benefits from using 3rd generation improved seeds, relative to BAU scenario (Millions of C$).

	TB			GATB		
	Changes in PS	Changes in CS	Total benefit	Changes in PS	Changes in CS	Total benefit
(a) Annual Average Undiscounted Benefits, 2016-2053						
AB	8.54	0.12	8.66	177.12	2.50	179.62
BC	-0.72	0.11	-0.61	-14.76	2.32	-12.44
ROC	-0.57	0.25	-0.32	-11.71	5.10	-6.61
ROW_ex	-3.29	1.24	-2.04	-67.16	25.42	-41.74
U.S.	-1.61	3.23	1.62	-32.94	66.06	33.12
ROW_im	-5.71	7.20	1.49	-116.47	147.02	30.55
(b) Annual Average Discounted Benefits, 2016-2053						
AB	1.92	0.03	1.95	55.62	0.79	56.41
BC	-0.16	0.03	-0.14	-4.63	0.73	-3.91
ROC	-0.13	0.06	-0.07	-3.68	1.60	-2.08
ROW_ex	-0.74	0.28	-0.46	-21.09	7.98	-13.11
U.S.	-0.36	0.73	0.37	-10.34	20.75	10.40
ROW_im	-1.29	1.62	0.34	-36.58	46.17	9.59

† Note: The total benefit is the sum of changes in consumer and producer surplus. All values in Panel a and b are expressed in real 2015 dollars. Values in Panel b are discounted to 2015 present values using a real discount rate of 4% per annum.

In this 3rd generation IS scenario, the annual average (discounted) total benefit of GATB is almost 30 times higher than the benefits generated by the TB approach. This is because in this case, by assumption, GATB not only can achieve higher genetic gain due to the higher selection accuracy effect but this scenario also has a 16-year R&D time-saving compared to

TB. Therefore, to produce the 3rd generation IS, it is beneficial to adopt GATB. Similar to the previous results, if IS produced using TB and GATB are used in AB, consumers in all regions and AB producers are better off while producers in other regions are worse off; and the supply shock in AB has a negligible impact on other regions.

3.5.2.5 Sensitivity Analysis

The extent to which the genetic volume gain can be transferred into the ACE depends on the government's decision. For example, even if the genetic gain achieved using GATB is 30%, the government may only allow for 6% genetic gain to be transferred into the ACE, and therefore the actual increase in timber supply may be less than expected. To address this concern, I do sensitivity analyses around the level of genetic gain that will be transferred into the ACE based on the last two breeding strategies (i.e., using TB and GATB to produce the 3rd generation IS).

As expected, the higher the level of genetic volume gain that can be transferred into the ACE, the higher the economic returns to the TB and GATB research (Figure 3.8). Since the R&D costs of TB and GATB are fixed no matter what the level of genetic gain is, the net returns are increasing at a faster rate as the level of genetic gain increases. At all levels of genetic gain, GATB generates significantly more economic benefit than TB (Figure 3.8). The range of the expected net returns for the GATB research is 126 C$ million-2127 C$ million. That means even if only 6% genetic gain can be transferred into an ACE, there is a positive (discounted) net benefit of 126 C$ million to Alberta across all pine and spruce programs. However, in the case of TB research, if only 6% genetic gain can be transferred into the ACE, the economic benefits is unable to offset the R&D cost of TB and the net present value of total benefits is -2 C$ million. In the case of TB, even if 30% genetic gain can be transferred into the ACE, the net present value of total benefits is still lower than the minimum amount of expected economic benefits in the case of GATB when only 6% genetic gain can be transferred into the ACE (83 C$ million < 126 C$ million). This finding again indicates that the main driving factor of the economic benefits is the time saved during the breeding process instead of the level of genetic gain. By assumption, the R&D investment time of GATB is 16-years shorter than the R&D investment time required by

TB. The results imply that the economic benefits associated with TB are highly discounted over the decades-long R&D process while GATB can capture more benefits due to its shorter breeding cycle.

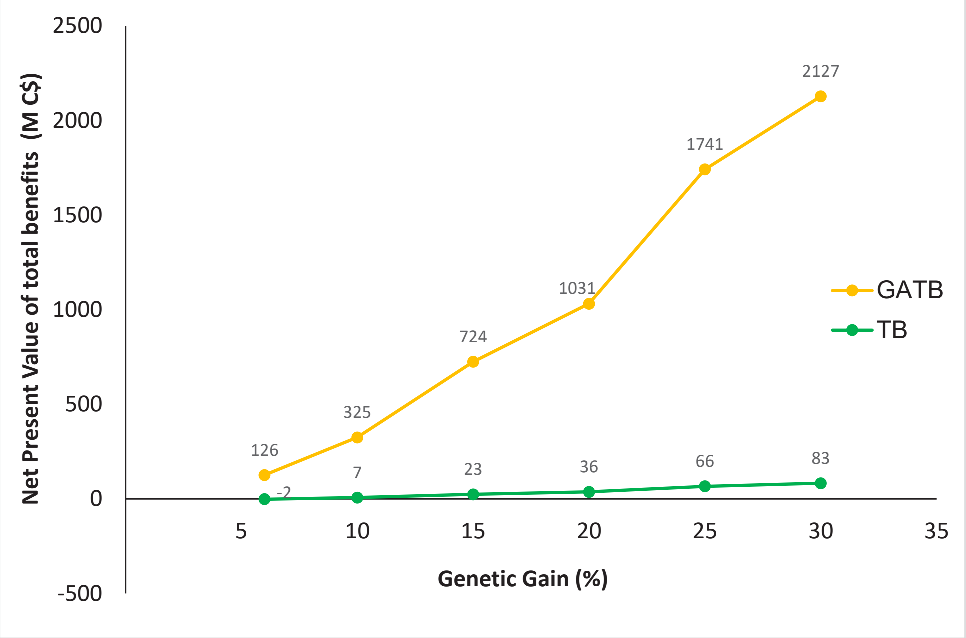

Figure 3.8: Net present value of total benefits of 3rd generation IS produced by TB and GATB as the level of genetic gain varies, Alberta, 2016-2053, discount rate=4%. TB refers to traditional tree breeding; GATB refers to genomics-assisted tree breeding.

Other uncertain factors, such as the deployment area of IS, can also significantly affect the economic surplus results. To gauge the potential effect of adoption rate on the economic returns, I also conduct a sensitivity analysis around alternative adoption rate of IS and level of genetic volume gain. This sensitivity analysis is based on the last breeding strategy (i.e., adopting GATB to produce the 3rd generation IS) as previous results show that this breeding strategy generates the highest returns.

As shown in Table 3.11, magnitudes of impacts are sensitive to both the adoption rate and genetic gain levels. In present value terms, the estimates of returns to R&D from GATB range from -113 C$ million (40% adoption rate and 6% genetic gain) to 2127 C$ million (100% adoption rate and 30% genetic gain). In the majority of cases represented in Table 3.11, the present value of benefits is significantly greater than the present value of total GATB R&D costs over the period of 2016-2053. However, the economic returns are negative when only 6% genetic gain is transferred into the ACE and less than 60% of the reforestation area is deployed with IS or when 10% genetic gain is transferred into the ACE and less than 40% of the reforestation area is deployed with IS.

Table 3.11: Discounted economic returns (Millions of C$) of adopting GATB to produce 3rd generation IS as the deployment area and the level of genetic gain vary.

Adoption rate (%)	Genetic Volume Gain at Rotation (%)					
	6	10	15	20	25	30
100	126	325	724	1031	1741	2127
80	28	171	518	677	1197	1516
60	-16	28	325	416	724	983
40	-113	-69	126	225	325	472

† Note: Adoption rate refers to the percentage of total reforestation area in Alberta that is deployed with 3rd generation IS produced using GATB. All values are expressed in real 2015 dollars. Values are discounted to 2015 present values using a real discount rate of 4% per annum.

3.6 Discussions and Conclusions

In this chapter, I investigate the *ex ante* economic effect of adopting genomic technology in the Alberta forest sector. I do so in two steps: first, I construct a timber supply model using a forest management modeling system to quantify the ACEs associated with different breeding strategies. Second, I incorporate the simulated ACE results into a spatial equilibrium model to calculate the economic benefits and net returns associated with each breeding strategy. The spatial equilibrium model is calibrated to observed bi-lateral trade flows of SWL in 2015 using positive mathematical programming.

From Alberta's perspective, my results indicate that the payoffs of GATB research are large, even though the innovation process entails relatively long lags in research before benefits begin to be realized in the field compared to other agriculture R&D innovations (e.g., see Weaber and Lusk, 2010). Magnitudes of economic impacts vary significantly across different breeding strategies because of differences in R&D lags and genetic gain levels. I find that the net returns to GATB are significantly higher than TB, especially when there is a time-saving effect. In particular, my results demonstrate how changing the R&D lag can very substantially change the present value of the benefits. All else being equal, technologies that are available sooner will have greater benefits. The impact of Alberta SWL supply shocks on global markets is extremely small due to its relatively small market share. For all breeding strategies, the major beneficiaries of the surplus economic benefits generated are Alberta producers and consumers in all regions. While producers in other regions will see a net loss, the magnitudes of the loss are small.

The future of GATB and the implementation of the ACE policy are quite uncertain and the expected benefits from GATB will greatly depend on the adoption rate of IS and the level of genetic gain that can be transferred into the ACE. As shown in Table 3.11, there are certain conditions under which the economic returns associated with GATB are negative. It is more likely to generate negative economic returns when the adoption rate of IS and the genetic gain level that can be transferred into an ACE are low. Currently in Alberta, only about 15% of the reforestation area is deployed with IS and generally less than 5% of the genetic gain can be transferred into the ACE. If this current situation continues into the future, the benefits of GATB may not be able to offset the R&D costs. However, in 2016, Alberta published a new directive which requires that where artificial reforestation activities are approved to occur, timber disposition holders must use IS made available for sale from approved Controlled Parentage Program seed orchards (Alberta Agriculture and Forestry, 2016). Thus, the adoption rate is expected to be higher than 40% in the near future. Previous study argues that the ACE has been largely unsuccessful due to the rent collection provisions that prevent firms from achieving enough financial returns on investment, temporal harvesting regulations as nonbinding constraints, the high costs of having an ACE approved and uncertainties surrounding crown tenure right (Luckert and Haley, 1995). Given the potentially large economic benefits, the Alberta government may consider a less stringent ACE policy that allows for a greater proportion of genetic gain of IS to be transferred into an ACE and therefore provides more incentives for forest companies to invest in silviculture activities on public lands.

Chapter 4: Conclusions

4.1 Summary of the Study

This thesis presents two studies that look at the historical productivity growth of the Alberta logging industry and R&D in genomics that can potentially increase future productivity of the forest sector. Specifically, two research questions are investigated: (1) how have rates of technical change and total factor productivity growth of the Alberta logging industry evolved over time and how have government regulations affected the productivity of the industry? (2) if genomic technology can help increase the productivity of forest lands, what is the economic returns to genomics R&D from an economic point of view and how will government policies affect the potential payoffs?

I answer the first question in Chapter 2 by examining the production structure of the Alberta logging industry. Based on the duality theory of production and cost, an unrestricted translog cost function and five restricted cost functions are each estimated simultaneously with the cost share equations using the Iterative Zellner method. The Allen and Morishima elasticities of substitution among pairs of inputs and price elasticities of factor demands are computed. The difference between the rate of technical change and the total factor productivity growth is discussed, and both are calculated. This study uses annual data of output and four inputs (i.e., labour, capital, energy and materials) from 1981 to 2012. The key finding, based on the sample used, is that both the rates of technical change and total factor productivity growth are negative in most years. This finding support previous arguments that stringent forest management regulations in Alberta discourage innovation and hinder competitiveness (Haley and Nelson, 2007; Kant, 2009; Vertinsky and Luckert, 2010). I also find low elasticities of substitution between inputs and that technical change has been material-neutral. Given the material cost is more than half of the total production cost, it may be beneficial to invest in technologies that increase timber productivity.

I answer the second question in Chapter 3 by examining how changes in growth and yield of the forests affect the AACs of forest companies and ultimately economic surplus of SWL producers and consumers. Research in traditional breeding (TB) and genomics-assisted tree breeding (GATB) produces improved seeds (IS) with higher genetic volume gain (i.e., higher yield) at a rotation age. In Alberta, the genetic volume gain of IS can be transferred into an ACE which allows forest companies to harvest more timber immediately even though the actual increase in forest yield will occur in the future. Assuming a fixed lumber recovery factor, production of SWL would increase as the timber supply increases. Therefore, timber and SWL supply shifts in Alberta will affect the market prices and welfare results. This study mainly involves two steps: the first step is to construct a timber supply model to simulate the ACEs associated with different breeding strategies, and the second step is to employ a recursive spatial partial equilibrium model to investigate welfare effects associated with the ACEs. A baseline forecast from 2016 to 2053 is first projected and then compared with four alternative scenarios: (1) using TB to produce the 2nd generation IS; (2) using GATB to produce the 2nd generation IS; (3) using TB to produce the 3rd generation IS; (4) using GATB to produce the 3rd generation IS. A comparison of the simulated scenarios with the baseline projection reveals the economic benefits caused by TB and GATB research.

The study presented in Chapter 3 also shows that it is beneficial to use the ACE policy instrument to encourage investment in tree improvement in Alberta because the simulated ACEs in all breeding scenarios are positive and therefore lead to positive economic returns. I also find that using GATB to produce the 3rd generation IS generates the highest economic returns due to the existence of both a higher selection accuracy effect and a shorter breeding cycle effect. The sensitivity analysis results indicate that the main driving factor of the economic returns is the time saved during the breeding process. A main conclusion I draw from this study is that integrating genomic technology into current tree improvement programs can be beneficial. However, if the government decides to not approve an ACE or only approves a small proportion of the genetic volume gain, the economic benefits associated with GATB may not be able to offset the R&D costs.

4.2 Implications of the Study

Regarding the economic research problems described in section 1.3, the analysis of the potential relationship between government regulations in the Alberta forest sector and the negative productivity growth results supports the hypothesis that government regulations increase production cost, reduce competition and therefore discourage technical change and constrain productivity growth over time. The wide range of potential economic returns to GATB R&D associated with the ACE policy indicates that government policies can have a significant effect on welfare outcomes of technology adoption. The uncertainties associated with the implementation process of a policy (e.g., the extent to which the volume gain can be transferred into an ACE) can limit the benefits of a new technology and hinder the technology adoption process.

The results of this study have a number of important implications. First, the government may want to provide greater flexibility to forest companies to encourage technical change and maintain competitiveness of the forest sector. While the government intends to use the ACE as a policy instrument to encourage private investments in silviculture activities, the actual effects of the ACE have not been significant in the past. The results of this study show that there are potentially large economic benefits associated with the ACE policy, indicating that there is room for the Alberta government to adjust the use of the ACE so that the forest companies have more incentives to adopt new technologies and the forest sector can be better off than the status quo.

Secondly, it is beneficial for forest companies to replace current TB techniques with GATB because the economic returns associated with GATB is shown to always be higher than TB, regardless of how the ACE policy is implemented. Traditional breeding requires decade-long phenotyping for each cycle of breeding which is associated with high risks and uncertainties. The genomic technology can be seen as a powerful tool to overcome this challenge as GATB does not require phenotying after the first breeding cycle, and therefore can shorten the breeding cycle by up to 20 years in cycle two and possibly three, which is a main driving factor of economic returns. Another important finding is that once the genetic volume gain that can be transferred into an ACE is greater than 15%, the GATB R&D cost becomes insignificant. For example, when the genetic volume gain that is transferred into an ACE is 15%, even if only 40% of the provincial reforestation area is deployed with IS, the benefit-cost ratio is almost nine, indicating that for each dollar of funds invested in the GATB research program, the result is almost a $9 benefit. This measure again provides evidence that the economic rate of return to genomic research in the forest sector can be high. While the cost of genotyping has decreased significantly over time, the phenotyping cost is constantly increasing as a result of the increasingly expensive labour. This factor also favours the adoption of GATB.

4.3 Limitations of the Study

In terms of the research on technical change and productivity growth in Chapter 2, the major limitation is that the effect of more stringent policy on productivity is not tested directly by incorporating a policy stringency parameter in the cost function. It is difficult to measure "regulation stringency". One possible approach is to count regulations, such as counting page numbers of regulation documents (De Rugy and Davies, 2009) and counting the number of binding words (e.g., shall, must and required) that appear in the regulation documents (Al-Ubaydli and McLaughlin, 2017). This approach assumes that the more regulations there are, the more regulated an industry must be. Another approach is to create a regulation index. Given the time limits on this research, the impact of regulatory policies on productivity is not explicitly accounted for in this study. There are also some other limitations that should be addressed. First, while output is constrained, the assumption of total cost minimization may be too strong as the logging industry relies heavily on highly specialized and nontransferable capital stock. Second, simultaneity problems may exist as the AAC is fixed but not always binding[1]. Given the simplified structure of the model de-

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[1] In Alberta, the AAC is defined as the maximum volume of timber that can be harvested and the sustained yield policy in Alberta allows for some harvesting flexibility around the AAC (Hegan and Luckert, 2000). For example, the tenure holders can harvest within ±25% of the AAC as long as the 5-year harvest totals are within ±10% of the 5-year allowable cut (Hegan and Luckert, 2000).

veloped in this study, several extensions can be topics for future research, such as explicitly accounting for the impact of specific regulatory policies; relaxing the assumption of long-run cost minimization; and comparing the productivity across different regions of the world.

There are also several limitations associated with the *ex ante* economic impact assessment of adopting GATB in Chapter 3. First and foremost, I assume the genomic technology is yield-enhancing with certainty and my study is based on expected genetic volume gain as the genomics R&D is ongoing and the actual volume gain is unknown. To increase the accuracy of the results, an *ex post* assessment should be done once the efficacy of the genomic technology has been tested in the field. Second, due to a lack of spatial forest inventory data, the timber supply analysis and the calculation of the ACE are simplified using provincial level non-spatial forest inventory data. A study that is at the forest management area level and uses spatial forest inventory data can be more informative. Third, the effect of timber processing capacity limitations on the supply behavior is not captured. Future study can address this issue by incorporating the capacity constraints of mills into the model. Fourth, I only consider a volume gain as a result of tree improvement programs and ignore other changes associated with the use of genomic technology. For example, in some cases, as the volume increases, other quantitative trait, such as wood density, might be negatively affected (El-Dien, 2017). The extent to which the decreased wood quality will affect wood values is not considered in this study. Future studies may mitigate this limitation by considering the quantity-quality trade-offs caused by tree improvement R&D. Lastly, this study assumes a fixed adoption rate. In reality, the adoption rate is more likely to increase over time. Future research may incorporate an adoption pattern of genomic technology (e.g., logistic growth) into the model.

Since I only consider the impact of a yield-enhancing trait (volume) in white spruce and lodgepole pine in this study, future *ex ante* impact assessments should evaluate other traits such as disease-resistance and drought tolerance traits. There might also be a demand shift due to consumers' perceptions regarding the use of genomic technology. Future studies can incorporate this societal acceptance factor by interviewing wood product consumers to ascertain their willingness to pay for a desired trait created using genomic technology. Another issue that deserves further evaluation is the technology spillover effect. My analysis assumes genomic technology is adopted exclusively in Alberta and focuses on the direct effect of GATB on increasing timber supply and social surplus in Alberta. However, to the extent that spillover effects increase the adoption of genomic technology in other regions, the total benefits to Alberta may decrease. For example, it is likely that the genomic technology will be adopted in BC at the same pace as Alberta, if not faster. This is because BC has a larger forest sector and has invested much more in R&D in forestry genomics than Alberta. The annual timber volume harvest in BC is almost two times more than the harvest in AB (Natural Resources Canada, 2017) and Genome BC has invested in eleven large-scale forestry genomic projects while Genome Alberta has only invested in three similar projects to date with only one led by Genome Alberta (Genome Canada, 2018).

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Appendix A: Breeding Strategies

A.1 Reforestation with 2nd generation improved seeds

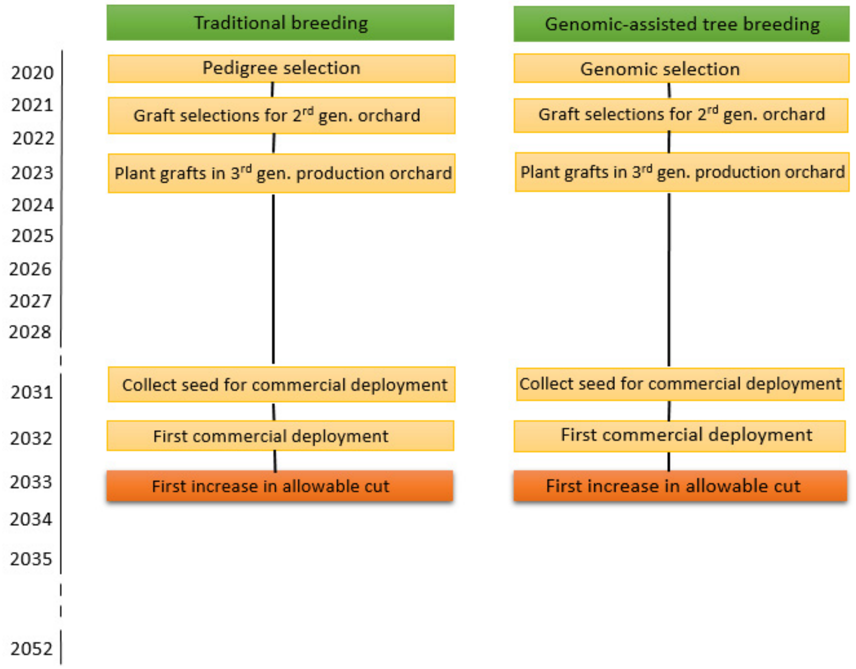

Figure A.1: Pathways of producing 2nd generation seed orchards using TB and GATB.

The purpose of Figure A.1 is to show the pathways of developing 2nd IS and compare the economic benefits of using TB and GATB. For most tree improvement programs in Alberta, first generation seed orchards are already well developed using TB. To develop 2nd generation seed orchard, both TB and GATB techniques can be used. TB is based on pedigree selection while GATB is based on genomic selection which is demonstrated to be more accurate than pedigree selection (Porth et al., 2015; Ratcliffe et al., 2017). Since the first generation testing is already done, the genomic tool cannot be used to shorten the breeding cycle in this case. Thus, as shown in Figure A.1, the only difference between TB and GATB is the selection methods (i.e., pedigree versus genomic selection) which lead to different levels of genetic gain. I assume that TB produces IS with 15% genetic gain and GATB produces IS with 20% genetic gain. In both cases, the first increases in allowable cut are projected to occur in 2033. In this scenario, GATB is only associated with higher selection accuracy effect.

A.2 Reforestation with 3rd generation improved seeds

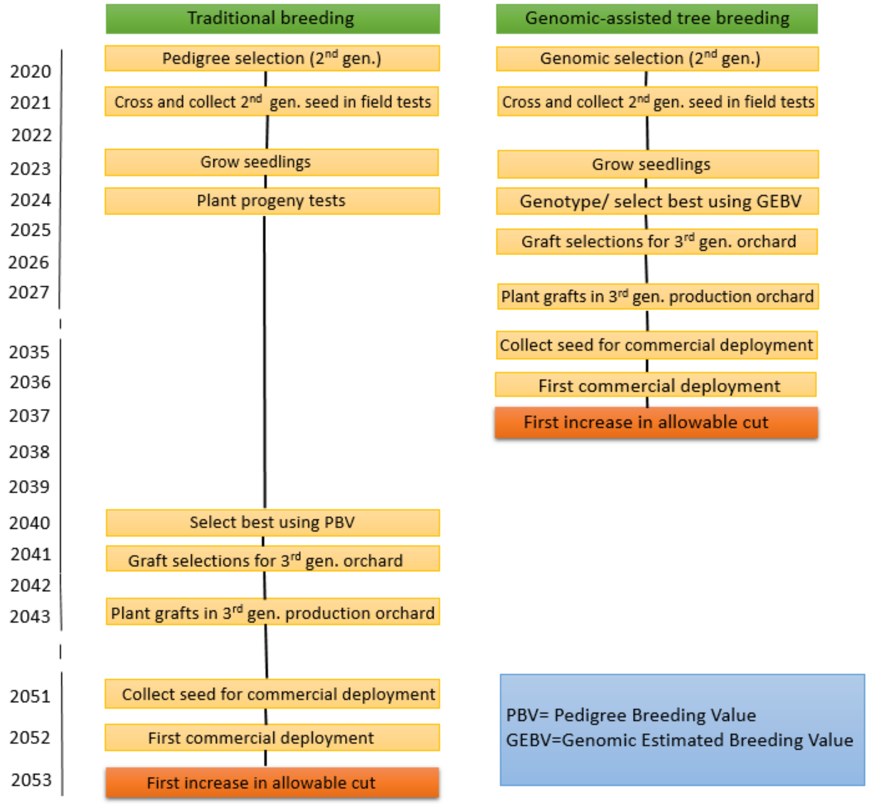

Figure A.2: Pathways of producing 3rd generation seed orchards using TB and GATB.

The purpose of Figure A.2 is to show the pathways of developing 3rd generation IS and compare the economic benefits of using TB and GATB. For both breeding strategies, it is assumed that researchers cross and collect the second generation seed in the field tests and graft a new third generation orchard to produce IS for reforestation. Compared with the TB approach, the genomic technology developed by the research program can be used to shorten the testing process by 16 years[1]. Additionally, using genomic selection can achieve higher genetic volume gain due to the higher selection accuracy effect. Therefore, I assume that TB can be used to produce IS with 25% genetic volume gain which can be used to increase allowable cut in 2053; GATB can be used to produce IS with 30% genetic volume gain which can be used to increase allowable cut in 2037. In this scenario, GATB is associated with both higher accuracy effect and shorter breeding cycle effect.

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[1] The actual time-saving range from 13 to 20 years.

Appendix B: R&D Costs

I consider two components of costs associated with TB and GATB research. The first component is the research cost which includes genotyping and/or phenotyping of the training population and the model development. The second component is the operational cost of seed production from seed orchards. I calculate the provincial level cost by multiplying the total cost per tree improvement by 15 because there are currently 15 white spruce and lodgepole pine tree improvement programs in Alberta.

The first breeding strategy (i.e., using TB to produce 2nd generation IS) involves pedigree select cost and seed production cost. There is no phenotyping cost because the first generation testing is already done. The second breeding strategy (i.e., using GATB to produce 2nd generation IS) involves model development and genotyping cost and seed production cost. The third breeding strategy (i.e., using TB to produce 3rd generation IS) involves both phenotyping cost and seed production cost. The last breeding strategy (i.e., using GATB to produce 3rd generation IS) involves model development and genotyping cost and seed production cost.

Table B.1: Research cost of phenotyping and genotyping per site

Activity	Total costs ($ CAD)	Total costs (%)
Phenotyping		
Seedling production	10250	3
Test design	500	0
Site search, survey, land reservation, planning	4133	1
Site development (e.g., fencing, weed control)	71943	24
Planting	32600	11
Establishment report, maps and db setup	2175	1
Maintenance (weeding, mowing, brushing)	4234	1
Herbicide application	7000	2
Data collection after planting (surv, condition)	4500	2
Data collection young age (ht, surv, cond)	40500	14
Data collection older age (ht, dbh, surv, cond)	108000	36
data preparation for analyses, measurement report	4229	1
Data analyses and report writing	8700	3
Model Development and Genotyping (for approximately 4800 trees)		
Tissue collection	50000	5
DNA extraction	88000	9
Genotyping by sequence (GBS)	456000	47
Computer Stations	265000	27
Bioinformaticians	118000	12

† Note: the total cost of each phenotyping item is the sum of the cost in each year for a period of 38 years. Cost per year is calculated by multiplying the cost per unit by the total number of units. For example: since site development cost only occurs in the first year, cost of site development is calculated by multiplying the cost per hectare ($20555 CAD) by total hectares (3.5 ha), which is $71943 CAD. Data sources: Government of Alberta.

Table B.2: Operational cost of seed production per seed orchard

Activity	Total costs ($ CAD)	Total costs (%)
Seed orchard (SO) design	4350	0
Forward selection (scion, wood, wood analysis)	30000	3
Seed collection and seedlot prep and tests	27100	3
Grafts production (rootstock, grafting, growing)	48140	5
Site search, survey, land reservation, planning	2742	0
Site development (fence, site logging, clearing, site prep)	36110	4
Layout and planting	5438	1
Irrigation system set-up	10000	1
Crown management	55000	6
Fertilization (materials and labour)	24800	3
Herbicide and pesticide spraying (materials and labour)	14000	2
PST monitoring phenology	33750	4
PST monitoring growth (every 2nd year)	3250	0
Pollen contamination	12150	1
Irrigation (water use)	14570	2
Maintenance and mowing	81530	9
Pest and disease monitoring	30000	3
Planning and reporting	67425	8
Roguing (thinning)	0	0
Cone collection, processing, extraction and Ne contribution	369863	42
Land opportunity costs (annual agricultural land lease rate)	7657	1

† Data sources: Government of Alberta.

Appendix C: An Example of the Timber Supply Simulation Output

Figure C.1 is an example of the timber supply simulation output from Woodstock. Note that the horizontal lines of all figures represent periods instead of years. The figure that indicates annual harvest volume is the allowable cut per period. Since I used 5-year period, the provincial level annual allowable cut would be one fifth of the annual harvest volume indicated in the figure. The left bottom figure indicates the change of growing stock over time. Due to the regulation that the amount of operable growing stock must be stable over the last quarter of the planning horizon, the quantity of grow stock is flat at the end. The first figure on the right describes the harvesting area of natural forest and second-growth forests over time. It shows that at the beginning of the planning horizon, the natural forest is planned to be harvested first. As the old-growth forests are exhausted, firms will start to harvest second-growth forests. The second figure on the right indicates that total forest area stays the same over time, but the natural forests will eventually all be harvested. The last figure on the right shows the age class distribution of the forest at a specific time. Woodstock users can choose to see the age class distribution of the forests in a particular planning period.

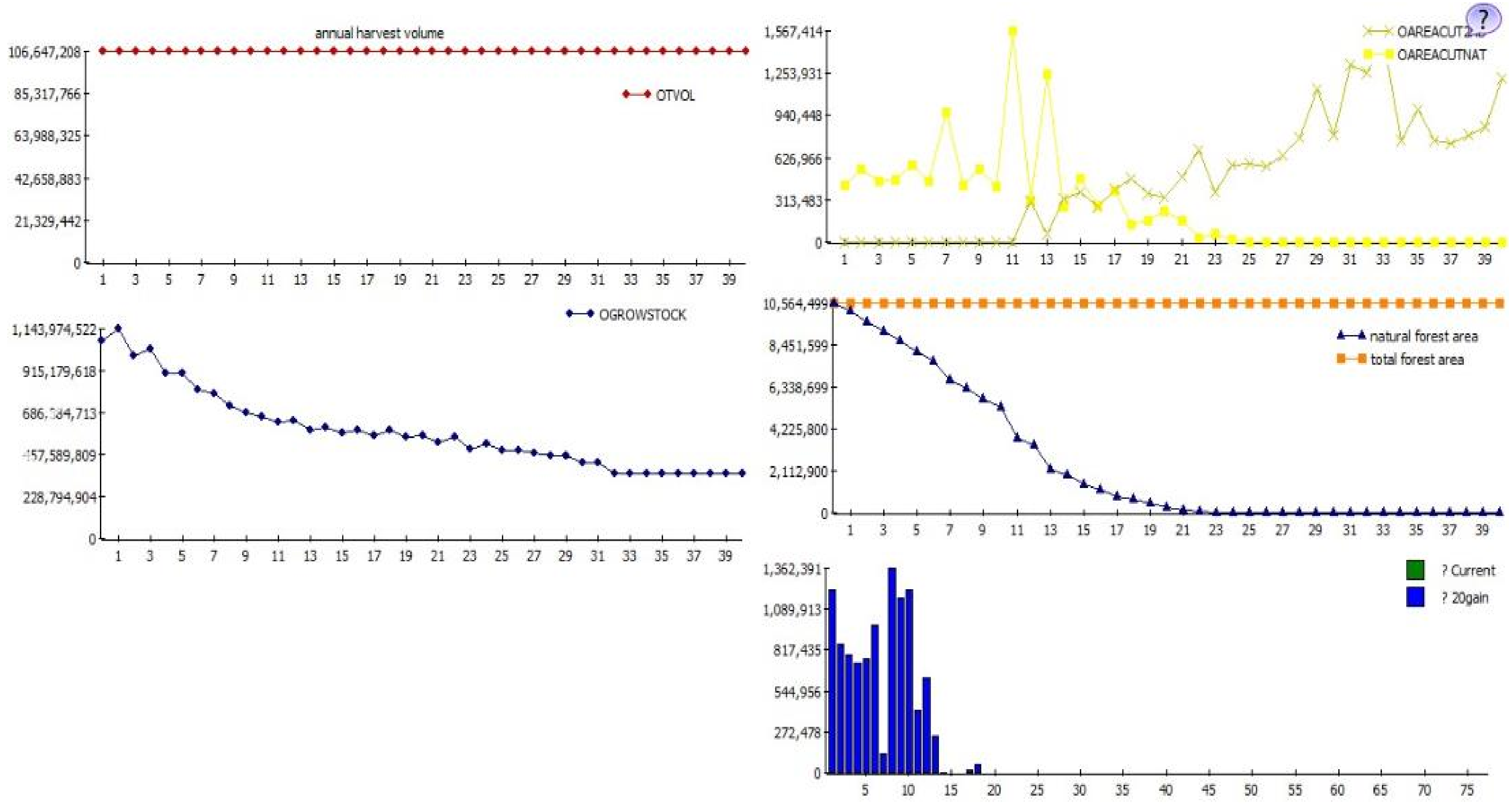

Figure C.1: Output of Woodstock when the improved seed used for reforestation has a 20% genetic gain.