SWST – International
Society of Wood
Science and Technology

Economic Evaluations of Tree Improvement for Planted Forests: A Systematic Review

BIOPRODUCTS
BUSINESS

Wei-Yew Chang[1*], Shuo Wang[2], Chris Gaston[1],
Julie Cool[1], Henry An[2], and Barb R. Thomas[3]

Abstract

This paper reviews the literature on the economic evaluations of tree improvement for planted forests and investigates whether or not using improved reforestation stock from tree improvement programs is a good investment. The main findings from systematic web-based searches show that (1) tree improvement is an effective tool to improve forest productivity and to realize financial returns; (2) economic gains from wood production with selection for breeding traits (e.g., high-volume yield or height growth) are the main reasons forest managers adopt new biotechnologies in tree improvement; (3) cost-benefit analysis is the primary empirical approach for estimating the economic effects of tree improvement for planted forests; and (4) there is very little literature on estimating the non-market benefits (e.g., improved watershed protection, amenities, or conservation of genetic diversity) that tree improvement brings, using non-market valuation techniques. The recent introduction of new biotechnologies in tree improvement, such as genomics-assisted tree breeding (GATB), can achieve genetic gains in selected traits more quickly and effectively than traditional breeding approaches, providing economic incentives for forest managers to use better quality stock for planted forests. Therefore, we suggest that future research should (1) consider the additional benefit, extra research and development costs, and time saved by applying new biotechnologies in tree improvement (e.g., GATB) in the cost-benefit analysis; (2) investigate the trade-offs between timber volume and wood quality traits and assess the economic effects of new biotechnologies in tree improvement along different stages of the forestry supply chain; and (3) explicitly account for the non-market trait values for the targeted breeding traits (e.g., drought/pest resistance) so that tree improvement programs can contribute to sustainable production systems. Economic analyses along these lines could help policy makers, forest managers, and forest company owners better understand the trade-offs of alternative breeding objectives and make economically efficient investment decisions for planted forests.

Keywords: economics, benefit-cost analysis, tree improvement, improved regeneration material, genetic gain

1 Introduction

Planted forests (FAO 2016) play an important role in sustainable forest management and can help to fulfill a wide variety of social, economic, and environmental objectives (Paquette and Messier 2010). With timber harvesting in natural forests restricted or banned in many countries, combined with an increasing demand for wood products resulting from continued growth in human populations and incomes, the world's planted forests have expanded significantly over the past 20 years, from 124 million ha in 1995 to 291 million ha in 2015, an increase of 135% (FAO 2015). In 2012, planted forests were estimated to contribute 46.3%, or 770.2 million m^3, of the world's industrial roundwood production, and projections indicate that the world's planted forests could increase production to 75% of the global industrial roundwood demands by 2030 (FAO 2015, Payn et al. 2015). In addition to increasing the availability of wood to consumers, planted forests also provide key ecosystem services, helping to preserve the world's remaining primary forests and sequester a significant

---

1 Department of Wood Science, University of British Columbia, Vancouver, BC.
2 Department of Resource Economics and Environmental Sociology, University of Alberta, Edmonton, AB.
3 Department of Renewable Resources, University of Alberta, Edmonton, AB (ORCID: 0000-0002-9718-9297).
* Corresponding author. Email: changwy@mail.ubc.ca; Tel: 1-604-363-2821.

Acknowledgments: This work was supported by Genome Canada; Genome Alberta through Alberta Economic Trade and Development; Genome British Columbia; the University of Alberta; and the University of Calgary. Further cash funding has been provided by Alberta Innovates BioSolutions; Forest Resource Improvement Association of Alberta; and the Forest Resource Improvement Program through West Fraser Ltd. (Blue Ridge Lumber and Hinton Wood Products) and Weyerhaeuser Timberlands (Grande Prairie and Pembina). In-kind funding has been provided by Alberta Agriculture and Forestry; Blue Ridge Lumber West Fraser; Weyerhaeuser Timberlands Grande Prairie; and the Thomas, Wishart and Erbilgin labs in support of the Resilient Forests (RES-FOR): Climate, Pests & Policy – Genomic Applications project.

BioProducts Business 4(1), 2019, pp. 1-14. ISSN 2378-1394.
https://doi.org/10.22382/bpb-2019-001

proportion of the carbon caused by human activities (Paquette and Messier 2010, Sedjo 2001).

As forests become more common, it makes economic sense to improve the quality of seed and subsequent seedling stock used in planted forests, which includes planting improved (superior) trees rather than planting the same unimproved seed and seedling stock year after year. Using improved seedling stock also creates economic incentives for investors to pursue plant domestication and tree improvement activities to capture the benefits of these improvements and innovations (Sedjo 2003). Tree improvement is the application of genetic principles to increase the value of trees (Frampton 1996). Many traditional breeding programs throughout the world were initiated in the 1950s and involved selecting superior (plus) trees, breeding or simply collecting seed from these selected trees, and testing the progeny for the desired traits (Zobel and Talbert 1984). Since the 1990s, biotechnologies such as tissue culture, cloning, marker-assisted selection, and genetic modification/transgenics programs have been developed and introduced to forestry (Sedjo 2003), and more recently, genomic selection (Grattapaglia and Resende 2011, El-Dien et al. 2016, Ratcliffe et al. 2015, 2017). While the use of biotechnology has the potential to improve trees by enabling foresters to achieve gains in selected traits – such as greater volumes or better wood quality – more quickly and effectively, the key question before any specific program can be implemented is "What exactly will the benefits be?" Private woodlot owners and investors may be more interested in the potential (financial) profitability of the program, while policy makers will also consider the societal benefits.

In order to consolidate the knowledge that exists about the financial and societal benefits generated from tree improvement programs, we conducted a systematic review of existing literature on the economic analysis of employing tree improvement as a management option for planted forests. Our main questions are as follows: (1) Are there economic/financial benefits of using improved reforestation stock from tree breeding and improvement programs over the use of unimproved reforestation stock? (2) What are the most common evaluation methods for assessing the economic returns of using improved planting stock for planted forests? (3) What are the knowledge gaps in the existing literature, and (4) What are the challenges and issues that may affect the economic evaluation of employing tree improvement for planted forests?

2 Document Acquisition

To acquire the related literature for review, our search utilized both keyword-driven and manual approaches, following Tong et al. (2016). Specifically, we first conducted several systematic web-based searches using keywords and Boolean operator in the ISI Web of Science Core Collection database. The Boolean search was built on the following keywords: "Economic*" ("financial*" or "benefit*") AND "tree improvement*" OR "planting stock*" OR "genetically improved*" OR "forest genomic*" OR "regeneration*". A manual approach with a snowball technique was also conducted to carefully go through the reference lists of selected articles that included major research questions of interest for our investigation. We collected and focused on peer-reviewed literature in English that was published between 1988 and 2018. Articles that did not have empirical research on an economic analysis of the use of improved reforestation material from tree improvement were excluded from the systemic review.

In total, 15 studies were identified. The studies were located in seven countries: Canada (5 studies), the United States (1), Finland (3), Sweden (2), the United Kingdom (2), New Zealand (1), and Australia (1). Under the category of tree species, most studies (14 articles, >90%) focused on the examination of softwood species, and only one study focused on hardwood species. Among all of the studies investigated, the majority (11 articles, or 78%) focused on the economic analysis of the use of improved tree stock generated from conventional seed orchards *versus* unimproved materials (wild seeds); four studies (22%) investigated the financial incentives in comparisons of alternative tree breeding strategies (e.g., seed orchard, rooted cuttings, or genetic markers approaches) for planted forests. For economic evaluation methods, cost-benefit analysis is the primary empirical approach for estimating the economic effects of tree improvement for planted forests, which was employed in all of these studies and tended to focus on assessing the derived market (financial) benefits.

In the following sections, we introduce information needed to conduct a cost-benefit analysis of using improved stock from tree improvement programs for planted forests, followed by a literature review of the studies that we captured. Finally, we identify the main findings, knowledge gaps, and challenges and issues that should be considered in future economic analyses of applying forest tree improvement for planted forests.

3 Cost-Benefit Analysis of Tree Improvement Programs

Economic assessments of all forest management options should help forest managers and policy makers clarify objectives and choices while considering the trade-offs (McKenney 2001, Schreiber and Thomas 2017). Thus, when conducting an economic evaluation of tree improvement programs for planted forests, it is important to first identify the objectives of the tree improvements, which include the following: (1) identifying the selected breeding traits (e.g., genetic gain in volume yield, height growth, wood quality, or other characteristics related to biotic or abiotic resistance); and (2) clarifying the tree breeding objective for planted forests (e.g., for wood production use or non-wood use). Only then can appropriate economic tools for examining the economic effects of tree improvement programs be identified and conducted.

Cost-benefit analysis has been identified as the main analysis method by forest managers to estimate the benefits and costs of tree improvement programs and compare them with alternative options for planted forests, particularly with the objective of increasing wood production for commercial use (Schreiber and Thomas 2017). The impact of tree improvement research is reflected as a change in the biological growth function trait (volume), which is generally presented as genetic gain in percent of individual progeny or families when compared with an unimproved or average volume (calculated from the height and diameter at breast height) of the trees for a given population at a given rotation length. Gain improvement can be estimated by tree growth and yield models for stand-level impact projections or further incorporated into timber harvesting models for large-scale forest-level impact projections. Thus, it is the change in the value of the growth function that is relevant for an economic analysis of the biotechnology change in forestry (McKenney et al. 1992).

The information needed for conducting a cost-benefit analysis generally includes costs, stumpage prices, genetic gain of the breeding objective trait, and the general criterion for profitability. With that information, a worthwhile investment is one where the discounted or present value of all benefits, less all costs that occur through time, needs to be greater than zero (McKenney 2000). When compared with alternative reforestation materials, the economic efficiency of deploying new biotechnology in tree improvement for planted forests can be examined by comparing the maximum land expectation value with "unimproved" tree stock at the optimal rotation age (e.g., using wild seedling material from natural forests) and the maximum land expectation value with "improved" tree stock (e.g., using seedlings with better genetic quality from tree improvement programs) (McKeand et al. 2006, Ahtikoski et al. 2012). If the increase in land expectation value exceeds the additional (extra) seedling costs per hectare for better quality genetic material, there are economic incentives for tree growers and private investors to use improved seedlings for planted forests. The investment decision could also be justified on economic grounds (Pearse 1990).

4 Literature Review

Among all of the empirical studies that we captured, cost-benefit analysis was the most common approach to comparing the economic effects of alternative tree improvement programs for planted forests for which the objectives were to increase wood production (volume gained per unit time). The majority of authors concluded that using improved tree stock from these tree improvement programs for planted forests was a good investment when compared with unimproved reforestation material (see Table 1).

4.1 North America

Petrinovic et al. (2009) used a financial model to estimate the benefits produced by using improved white spruce (*Picea glauca* Moench) plantations in Quebec, Canada, with three different tree breeding methods: (1) a traditional tree breeding program from a seed orchard (with 10% potential genetic gain in height relative to unimproved seedling stock); (2) a method using cuttings from superior families obtained from controlled crosses (15% height gain relative to unimproved material); and (3) a program that involved planting multiclonal varieties produced through somatic embryogenesis and selected from seed orchards using genetic markers (20% height gain relative to unimproved material). Factors related to the quality of reforestation sites (at site index [SI] 8 m

Table 1. Summary of cost-benefit analyses of tree improvement programs for planted forests

Country	Tree species	Genetic gain of selected trait vs. unimproved	Results	Is tree improvement a good investment?	Literature
Quebec, Canada	White spruce	10-20% in height growth	Up to CAD$712/ha net present value for using a genetic marker approach (at a 7% discount rate)	Yes	Petrinovic et al. (2009)
New Brunswick, Canada	White spruce	timber volume gain of 6.25-26.55 m^3/ha	Up to 12.5 benefit-cost ratio (BCR) at a harvest age of 40 (at a 4% discount rate)	Yes	Wu et al. (2015)
Ontario, Canada	Black spruce	8-16% in volume growth for seed orchard approach and 10-20% for clonal/rooted cutting approach	Tree improvement program can be break-even (i.e., BCR=1) at a stumpage price of CAD$10/$m^3$ for seed orchard approach and CAD$17/ m^3 for rooted cutting approach (at a 4% discount rate with 2000 ha annual planting)	No, due to the low stumpage prices (CAD$4.5/$m^3$) at the time	McKenney et al. (1989)
Ontario, Canada	Black spruce and Jack pine	8-16% in volume growth	Seed orchard program can break-even at a stumpage price of CAD$17/$m^3$ for black spruce and CAD$10/$m^3$ for jack pine (at a 4% discount rate with 1000 ha annual planting). Investing in a jack pine improvement program would generate more revenue per dollar than black spruce	Yes	McKenney et al. (1992)
Alberta, Canada	White spruce and Lodgepole pine	1-4% increase in volume growth per decade	CAD$7.4 million increased net present benefit under the scenario of 2% increase in volume gain per decade and 15% increase of area planted per decade (at an 8% discount rate)	Yes, if an allowable cut effect is considered	Schreiber and Thomas (2017)
Southern United States	Loblolly pine	7-21% in height growth	US$99-415/acre (US$245-1025/ha) of additional net present site value for using improved seedling materials that could increase the site index from 70-85 feet (at a 5% discount rate)	Yes	McKeand et al. (2006)
Finland	Scots pine	8.7-14.7% in height growth	Using mature 1st generation seeds could generate 44% and 38% more financial benefits per hectare than the use of unimproved seeds for tree growers and a sawmill, respectively, in South-Central Finland (at a 3% discount rate)	Yes	Ahtikoski et al. (2018)
Finland	Scots pine	15% in volume growth	Up to €2,849/ha net present site value (at a 2% discount rate)	Yes	Ahtikoski et al. (2012)
Northern, Finland	Scots pine	3-10% in volume growth	The net cost of seed orchard seeds was less than the cost of natural stand seeds with 7% yield growth and 15% better seed quality with a higher survival rate (at a 3% discount rate)	Yes	Ahtikoski and Pulkkinen (2003)
Northern, Sweden	Scots pine	4-10% in volume growth	Using improved planting stock on the most productive site could generate additional benefits (up to €1,956/ha) relative to unimproved material via the natural regeneration method (at a 1% discount rate)	Yes	Simonsen (2013)
Northern, Sweden	Scots pine and Norway spruce	7.5-26% in volume growth depending on breeding methods	Planting improved seedlings has a higher benefit-cost ratio (24.6) than the benefit-cost ratio of cloned seedlings (2.0) due to lower investment costs (at a 2.45% discount rate)	Yes	Simonsen et al. (2010)
United Kingdom	Ash, Sycamore maple, Wild cherry, and Sweet chestnut	10.7-65.8% in volume growth, depending on tree breeding methods.	£38/ha of additional net present benefit with simple mass selection approach and £100/ha with seed orchard method. No additional net present benefits with the use of clonal techniques, due to the relatively low timber price and the higher extra early costs of planting stock	Yes, but only for the simple mass selection and seed orchard methods	Palmer et al. (1998)
United Kingdom	Sitka spruce	31% extra better quality logs	Planting vegetation propagation stock could not be justified under the market conditions at the time (£150/ha extra planting stock cost, £5/m^3 log premium, and at 3-5% discount rate)	No, due to the high extra cost of rooted cutting method	Lee and Watt (2012)
New Zealand	Radiata pine	25% in volume yield and 5.6% in height growth	NZ$7,400-11,400/ha increased net present value for using highly improved tree materials and up to NZ$8.5 billion increased total economic benefits in New Zealand (at a 7% discount rate)	Yes	Kimberley (2015)
Australia	Radiata pine	20-25% in volume growth	AUD$927 million increased net present value using improved seedling materials in the 1990s	Yes	Wu et al. (2007)

and 12 m at age 25) and silvicultural regimes (with and without thinning) were also considered in the model to examine their influences on the net present value of benefits. While the study was examined from a private woodlot owner's perspective and did not specifically consider the costs associated with generating improved planting material, as these costs were assumed to be borne by the government in Quebec, the authors found that planting improved trees can have significant financial benefits to the forest industry as well as for private woodlot owners. In addition, forest site quality had a substantial influence on the benefits, and the optimal economic rotation age could be reduced by up to 9 years for improved white spruce selected by genetic markers.

From a private woodlot owner's perspective, McKeand et al. (2006) evaluated the benefits of improved loblolly pine (*Pinus taeda L.*) seedlings from a range of genetic gain levels and site productivity levels using a growth and yield model. The authors found that an increase in SI values (at base age 25 years) associated with genetic gains in height of 1.52 to 4.57 m (5 to 15 ft), which is equal to a height gain of 7% to 21% relative to unimproved material, from different site productivity levels would result in increases in the net present site value ranging from US\$124 to \$741 ha^{-1} (US\$50 acre^{-1} to over US\$300 acre^{-1}), depending on planting density (1794 and 1077 trees ha^{-1} or 726 and 436 trees acre^{-1}) and management regimes (with *versus* without thinning). Additionally, the optimal economic rotation age for planting improved loblolly pine was reduced with an increase in site quality and through domestication (pers. comm., S. McKeand to B.R. Thomas, November 2017). The results of the study suggested that private landowners should plant the best genetic material (seedlings with the greatest gain value) on the most productive sites and under the most intensive forest management regimes to realize the largest financial benefits.

Wu et al. (2015) conducted a cost-benefit analysis to examine the investment desirability of an established white spruce clonal seed orchard in New Brunswick, Canada, *versus* one that used wild stand (unselected) seeds. The authors used actual costs incurred in the establishment of the seed orchard and projected revenue increases from the realized genetic gain in volume growth. A growth and yield model projected volume gain for two rotation ages (40 and 50 years) and two silviculture management scenarios (with *versus* without commercial thinning). Compared to wild-stand seeds, using improved seedling stock would result in a timber volume gains of 6.25 to 26.55 m^3 ha^{-1}. The estimated results indicated that the white spruce seed orchard in New Brunswick was a very good investment for all scenarios when the discount rate was less than 6%, and that the estimated benefit-cost ratio could reach up to 12.5 when commercial thinning was applied and trees were harvested at 40 years of age, assuming a 4% discount rate.

McKenney et al. (1989) used a cost-benefit analysis to compare two tree improvement methods (i.e., the traditional seed orchard approach and the clonal forestry/rooted cuttings approach) for black spruce (*Picea mariana* (Mill.) B.S.P.) tree improvement in Ontario, Canada. The genetic gains in volume for the traditional seed orchard approach were assumed to be 8% and 16% over wild seeds and 10% and 20% volume gains over wild seeds for the clonal/rooted cutting approach. To assess the potential economic impact of tree improvement, the authors specifically separated the research and development costs from the operational costs of tree improvement activities. The difference in net present value between improved and unimproved plantations at optimal rotation ages was therefore compared with the research cost to determine the total net worth of tree improvement. The authors found that the clonal/rooted cutting approach was economically unattractive, due to the high cost of cutting production relative to the conventional seed orchard approach, despite the higher genetic gain that could be achieved. Under more favorable though less likely conditions (i.e., lower costs and/or greater gain), the authors found that the project could be beneficial for plantations of 200 ha or larger. Ultimately, the authors suggested that, in addition to obtaining increasingly better clones, tree improvement research should also be aimed at lowering the production cost of the rooted cuttings to allow clonal forestry to become economically attractive.

McKenney et al. (1992) further compared the economic attractiveness of black spruce and jack pine (*Pinus banksiana* Lamb.) seed orchard programs in Ontario, Canada, using a cost-benefit analysis. Genetic gains of 8% and 16% in merchantable volume relative to unimproved material were used for both black spruce and jack pine. The estimated results showed that both jack pine and black spruce improvement programs could be supported on economic grounds with just an 8% increase in volume gain, as long as stumpage prices exceeded CAD\$8 to 12 m^{-3} on the best quality site and assuming a 4% discount rate. Sensitivity analysis results also revealed that the total net present value of the jack pine seed orchard approach consistently outperformed the total value of the black spruce seed orchard approach for all scenarios. Thus, if government budgets are limited, investing in jack pine improvement programs would generate more revenue per hectare than black spruce in Ontario.

4.2 Europe

There have also been economic analyses of tree improvement programs in Europe. A recent study reviewed by Jansson et al. (2017) found that tree improvement programs in Scandinavia and Finland have resulted in increases in volume growth in the range of 10% to 25% relative to unimproved material for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. (Karst)). The estimated net present value associated with planting improved trees in the region yielded better returns on investment due to shorter rotation periods than those for unimproved forests. Ahtikoski et al. (2012) examined the financial performance associated with the use of improved Scots pine seedlings in Finland and found that the use of improved seedling material with a 15% genetic gain in volume growth relative to unimproved material from a 1.5 generation orchard was financially attractive for private woodlot owners in most parts of Finland. The net present value (– land expectation value) was calculated to be worth up to €2,849 ha^{-1} (US\$3,386 ha^{-1}) at a 2% discount rate, and the optimal rotation period would be reduced by 15 years with a 15% genetic gain in volume. Ahtikoski and Pulkkinen (2003) compared the financial attractiveness of using improved seeds from Scots pine seed orchards with seeds from natural stands in northern Finland from a tree grower's perspective. Considering an increase of 7% in timber volume and an increase of 15% in seed quality, with higher survival rates relative to natural stand seeds, the authors found that the net cost of orchard seed was less than the total cost of natural stand seed, assuming a 3% discount rate. Moreover, in another study conducted by Ahtikoski et al. (2018), who compared three types of improved Scots pine seedlots to unimproved seedlots on three different sites in Finland, the authors found that using improved Scots pine seed material (including mature 1st generation, juvenile 1.5th generation, and mature 1.5th generation) not only created financial benefits for tree growers but also provided financial incentives for a sawmill in Finland, with higher sawing yield than that of unimproved trees.

In Sweden, the profitability of using improved planting stock to increase forest growth has also been investigated by Simonsen et al. (2010). The authors examined several silvicultural measures to increase the forest growth of Scots pine and Norway spruce for a forest company in northern Sweden and found that the use of improved planting stock generated from seed orchards is highly profitable, due to low investment costs and considerable increase of forest growth relative to other silvicultural measures, such as fertilization, treatment against insects, and improved seed quality. Under the scenario of planting improved stock with a 15% volume gain for Scots pine and a 7.5% volume gain for Norway spruce over wild seeds on average productivity sites, the estimated benefit-cost ratios for planting improved Scots pine and Norway spruce were 24.6 and 19.4, respectively, at a 2.45 discount rate. In addition, when the use of improved stock from different tree breeding methods was further compared, the authors found that planting improved seedlings generated from traditional seed orchards could have a much higher benefit-cost ratio relative to the use of cloned seedlings (i.e., 24.6 *versus* 2.0). Simonsen (2013) further compared the profitability of regenerating Scots pine in northern Sweden with two alternative regeneration methods (natural regeneration *versus* planting) and found that using improved planting material from seed orchards could greatly shift the preference towards the planting method. Specifically, under the scenario of using improved planting stock with a 10% volume gain over unimproved material, planting improved material could generate an additional US\$ 2211 ha^{-1} (€1956 ha^{-1}) on the most productive site (SI 28 m at age 100) at a 1% discount rate, when compared with the natural regeneration method. Moreover, the authors found that planting improved stock could enable landowners to break-even on lower productive sites, compared with the natural regeneration approach.

In the U.K., Palmer et al. (1998) assessed the financial benefits of planting four broadleaved tree species (i.e., ash [*Fraxinus excelsior* L.], sycamore maple [*Acer pseudoplatanus* L.], wild cherry [*Prunus avium* L.], and sweet chestnut [*Castanea sativa* Mill.]) using three different tree improvement methods: (1) simple mass selection (with up to 10.7% timber yield gain relative to unimproved material); (2) untested clonal seed orchards (up to 32.6% in timber yield gain relative to unimproved material); and (3) mass vegetative propagation (i.e., clonal) techniques (up to 65.8% timber yield gain relative to unimproved material). The estimated results showed that conventional selection methods (e.g., collecting seed from simple, mass-selected parent trees and the seed orchard method) were found to be more cost-effective than the use of clonal techniques, due to the relatively low timber price at the time. Therefore, the increased revenue from the improved stock was found to be insufficient to compensate for the higher extra early costs of planting stock produced by the clonal propagation breeding technique, despite the higher genetic gains that could be achieved. Another study conducted by Lee and Watt (2012) compared the financial returns of planting improved Sitka spruce (*Picea sitchensis* [Bong.] Carr.) stock derived from seed orchards with more expensive rooted cuttings through the vegetative propagation method in the U.K. The authors assumed that the predicted growth rates of seed orchard and vegetative propagation stock were the same; however, improved wood quality traits (such as stem straightness and branching quality) were observed from the vegetative propagation planting stock. The improvements in quality traits were further translated through the increased proportion of quality logs (i.e., extra 31% green logs relative to unimproved stock) and log premium. While this study specifically considered wood quality traits in the economic analysis, the authors found that planting vegetatively propagated stock could not be justified on economic grounds due to the high extra cost of planting stock (£150 ha^{-1}) relative to orchard seed seedlings.

4.3 Oceania

Wu et al. (2007) reviewed the genetic improvement of radiata pine (*Pinus radiata* D. Don) in Australia and found that, compared to unimproved material, the genetic gain in volume of radiata pine at 15 years of age increased up to 33% from a first-generation seed orchard, while an average 20% to 25% volume gain at the age of 10 to 15 years was generally observed from most first-generation gain trials. The investment in radiata pine breeding in the 1990s had generated a net present value of US$ 670 million (AUD$927 million) through the increased volume productivity and genetic seedling quality of the plantations produced. The authors concluded that tree improvement programs had generated significant economic benefits for the Australian forest industries.

More recently, Kimberley et al. (2015) analyzed a series of large plot trials in New Zealand and quantified the realized genetic gain in radiata pine tree improvement. The authors found differences in volume yield and height growth between unimproved and highly improved seedlots of 25% and 5.6%, respectively. The realized genetic gains were then incorporated into a national growth and yield modelling system to project the log volume gain at the harvest age. The authors used these estimated results to calculate the economic value of logs harvested at 30 years and found that the moderately improved and highly improved varieties resulted in economic gains of US$2,030 ha^{-1} to US$3,654ha^{-1} and US$5,007 ha^{-1} to US$7,715 ha^{-1} (NZ$3,000 to NZ$5,400 ha^{-1} and NZ$7,400 to NZ$11,400 ha^{-1}), respectively. Extrapolating this gain in the harvest log value per hectare to the 1.57 million ha of plantation area in New Zealand and assuming a 7% discount rate, the total net present value of tree improvement programs in New Zealand was estimated to increase by US$2.4 to 5.8 billion (NZ$3.5 to 8.5 billion), depending on the specific improved planting materials. This study demonstrated convincingly that tree improvement programs have created substantial economic benefits for New Zealand.

Most cost-benefit analysis studies that we reviewed indicated that tree improvement was an effective tool that can be used by forest managers to improve forest productivity. Using better genetic quality seedlings for planted forests was a good investment for private woodlot owners and the forest industry when compared to unimproved seedling materials. Economies of scale will also be realized from harvesting larger trees at the optimal economic rotation age, as well as more timber volume per hectare. However, studies have also found that the additional (extra) costs associated with the tree breeding methods used to produce the reforestation material must not be too high; otherwise, the genetic gains required to achieve profitability would be unrealistic.

5 Discussion and Future Prospects

In summary, the existing literature on the economic effects of using tree improvement as a management option for planted forests tends to (1) focus on wood production use and estimate the market benefits of improving selected (market) traits such as volume yield or height growth in the cost-benefit analysis; (2) ignore non-market benefits (e.g., improved carbon sequestration, watershed protection, amenities, or conservation of genetic diversity) provided by tree improvement compared to unimproved reforestation material, as tree breeders generally do not account for the non-market trait values of the selected traits; and (3) lack consideration of the trade-offs between wood quality and timber volume quantity resulting from alternative breeding traits/strategies and previous studies generally were examined from a tree grower's perspective. In this section, we identify several challenges and issues that ought to be considered in future economic analyses of applying forest tree improvement to planted forests.

5.1 Long Breeding Cycle

In contrast to breeding programs for many agricultural crops, a traditional tree breeding program is considerably longer. The long rotation period of some conifer species (e.g., 60 to 110 years for lodgepole pine [*Pinus contorta* Douglas] and white spruce in western Canada) and the long breeding, progeny testing phase and seed orchard establishment that is required for commercial deployment reduce the present value of the expected benefits and increase the riskiness of the investment. Burgeoning new biotechnologies in tree improvement (e.g., genomic selection) can increase selection accuracy and improve the genetic gain of interest traits, but more importantly, genomic selection offers a new approach to mitigating the long investment horizon by substantially reducing the entire tree breeding cycle (e.g., by up to 20 years for white spruce in the boreal region of Canada) by shortening the progeny testing phase in particular (Porth et al. 2015, Porth et al. 2016). A recent report from Isik (2014) suggested that genomic selection in loblolly pine improvement in the southern U.S. could significantly reduce the breeding cycle time by half and increase genetic gains twofold per year. The potential time savings from integrating genomic selection into tree improvement programs also significantly reduces the ancillary resources required in each generation of tree breeding (e.g., personnel, site development, seedling production and planting, site maintenance, data collection and analyses). This benefit would provide strong economic incentives for investors to adopt new biotechnologies into tree improvement for planted forests.

However, despite the exponential – and continuing – decrease in the cost of genotyping (a component of implementing genomic selection) over the past 10 years, cost remains a major hurdle in employing new biotechnology tools in tree improvement for planted forests (Isik 2014, Poland and Rife 2012). Because there are no published studies that compare the financial returns of genomic-assisted tree breeding to traditional breeding programs for planted forests (Porth et al. 2015), there is a need to investigate the benefits of adopting genomic-assisted tree breeding when breeding cycle time as well as research and development costs are included in the cost-benefit analysis framework.

5.2 Wood Quality

The inverse correlation between wood quality (e.g., wood density) and quantity (e.g., growth rate in timber volume) traits continues to be a challenge for forest tree breeders (Jayawickrama 2001, Park et al. 2012). Improved trees with fast growth rates usually reach sawlog size at younger ages and therefore are harvested at shortened optimal rotation ages. However, younger plantation trees tend to have a larger proportion of juvenile wood to mature wood, with a lower wood density and higher microfibril angle than in older more mature trees, both of which negatively affect the strength and stiffness of dimensional lumber. For example, Kretschmann and Bendtsen (1992) found that dimensional lumber cut from the juvenile wood core has only 50% to 70% of the strength and stiffness of lumber cut from mature wood, depending on the species and grade, which can significantly increase the manufacturing cost of dimensional lumber.

McKeand et al. (2006) examined the benefits of planting the best loblolly pine in the southern U.S. and found that landowners might not receive the assumed stated stumpage prices for loblolly pine harvested at the shortened rotation ages (e.g., 17 instead of 20 years). This is because younger (15 to 20 year-old) plantation-grown loblolly pine trees have over 70% juvenile wood in their bole, which has much lower strength properties and a higher moisture content, resulting in lower stumpage prices compared with mature (25 to 30 year-old) trees. Thus, the authors (McKeand et al. 2006) suggested that a *price penalty* for harvesting younger trees could be considered in the economic analysis by developing stumpage price structures for planted forests that recognize the strength, moisture content, and wood quality properties of trees with different amounts of juvenile *versus* mature wood. Projected revenues can then be appropriately adjusted in the economic analysis that explicitly considers the quality traits, and optimal rotation ages can be modified if price penalties (premia) are imposed for trees with a high (low) percentage of juvenile wood (e.g., Petrinovic et al. 2009, Lee and Watt 2012).

Ahtikoski et al. (2012) and Jansson et al. (2017) commented that the inverse correlation between wood quality and growth rate from planted forests can be addressed in economic analyses by estimating the relative economic weights of different selected breeding traits in the profit function, which can be used as an index to measure the net economic gains derived from different selected breeding traits. According to Ivković et al. (2006a, 2006b) and Wu et al. (2007), there are six key steps to developing the optimal economic weights for breeding traits. However, this approach requires accurate information on growth rates and quality attributes, which is still difficult to obtain, according to Ivković et al. (2010) and Jansson et al. (2017). A simpler approach to quantifying the trade-offs that producers or end-users make between wood quantity and quality is the use of choice experiments or conjoint analysis, which is an experimental approach commonly used in the economics literature. For example, previous studies showed that negative genetic correlations are present between traits of interest; e.g., wood quality changes and log dimensions diminish because of faster growth rates (Evans 2009). Thus, the point at which the loss in wood quality exceeds the benefit from faster growth is an important economic question and may differ by species, stakeholder, and end user (see Vossler et al. (2012) and Holmes et al. (2014) for more specific econometric models, survey design issues, and sampling processes of the choice experiment method).

Economic analysis of tree improvement for planted forests, with respect to the wood quality issue, can also investigate the wood quality gains needed to justify a tree improvement program, if volume gains are not sufficient, through the use of sensitivity analysis under a cost-benefit analysis framework (McKenney et al. 1992). For example, if a given stumpage rate is not sufficient to justify tree improvement, then the difference between that stumpage rate and the break-even stumpage rate indicates the value of wood quality gain required to proceed with the project. This type of analysis could be complemented by expert surveys of geneticists/breeders and sawmill operators to gauge the likelihood of achieving the required gains as well as the costs involved (McKenney et al. 1992).

As tree improvement programs are shifting to target wood quality (and biotic resistance) traits instead of only growth rates, it is important to consider the economic impact across the entire supply chain and the potentially different distributional effects. For example, the way in which different breeding objective traits affect the profitability and production efficiency of sawmills will likely be different from how they affect the end user or the grower. Some sawmills may be willing to pay a price premium for logs of a particular age or with a minimum threshold density, and how these market signals are transmitted from processor to grower will affect planting and harvesting decisions (Ivković et al. 2006a). Moreover, of the 15 studies that we captured, only 1 study, conducted by Ahtikoski et al. (2018), investigated whether using improved reforestation material would create simultaneous benefits for tree growers and a sawmill in Finland. The remaining 14 studies were all investigated from a forest manager's perspective to examine the profitability of using improved stock for planted forests. Thus, a more comprehensive economic analysis of the entire supply chain that considers price pass-through, information feedback, and the effect of market power would help forest managers and the forestry industry better understand the trade-offs between the timber growth rate and wood properties and ensure better informed investment decisions regarding planted forests.

5.3 Non-Market Trait Values

Tree breeding and improvement programs traditionally focus on the genetic improvement of key production traits (e.g., height, diameter, and volume) that have clear economic values driven by short-term market forces, also called *market trait values* (Olesen et al. 2000). For example, the market trait values of using disease-resistant seedling material for planted forests can be evaluated through the increased timber volume gain multiplied by stumpage prices. However, to have long-term biologically, ecologically, and sociologically sound breeding goals for the efficient use of resources and sustainable production systems, researchers proposed that the non-market trait values should also be considered in breeding and improvement programs (Olesen et al. 1999, 2000).

Using animal breeding as an example, Olesen et al. (2000) suggested that implementing both market and non-market trait values in the aggregated genotype (i.e., total trait values) could contribute to sustainable livestock production systems. The authors proposed that changes in the quality and quantity of animal traits have value, as they either change the benefits associated with human activities or change the costs related to these activities, which have an impact on human welfare through established markets or through non-market activities (e.g., ethical values of improved animal welfare through less suffering from diseases or stress and a higher quality of life). The market value of the breeding traits could be reflected by the change in market prices, while the non-market value of the breeding traits could be reflected by improving the values of natural capital and ecosystem services by changes in traits (Olesen et al. 2000).

Compared to animal breeding, using improved seedling materials from tree improvement could provide stronger positive externalities (e.g., carbon sequestration, watershed protection, or amenities) relative to unimproved materials; however, these non-market benefits were generally not targeted by tree breeders in the past, as they are not contingent on changes to the key production (market) traits achieved via tree improvement programs. In the tree breeding context, planting disease-resistant trees might also increase the aesthetic and recreational values, increase carbon sequestration and reduce degradation of the atmosphere over unimproved planting stock. Such values should be represented by the non-market trait values in tree breeding and improvement programs. Thus, the traits' values in the aggregate genotype can be split into non-market trait values and market trait values (Olesen et al. 2000). The genetic gain in objective traits will also include a non-market genetic gain (e.g., carbon sequestration) and a market genetic gain (volume). Without considering the non-market trait values, the true trait values of tree improvement could be underestimated.

While non-market valuation techniques have been used to evaluate ecological goods and services provided by planted forests (see Table 2 for examples), to our knowledge, no existing literature has investigated the non-market trait values in forest tree improvement programs using these non-market valuation tools. Further adopting the idea of non-market trait values from animal breeding to tree improvement would provide a holistic perspective from which to evaluate the extra benefits that tree breeding brings to non-market benefits and to give the natural capital stock that produces ecosystem services adequate weight in the decision-making process (Costanza et al. 1997).

5.4 Climate Change

Another role envisioned for tree breeding programs and planted forests worldwide is mitigating anthropogenic global warming. For example, in Canada, global warming is expected to have a profound impact on Canadian forests, including planted forests, as tree growth responds directly to changes in CO_2 concentration, temperature,

Table 2. Valuation methods for non-market benefits associated with planted forests.

Valuation method	Value captured	Non-market benefits valued	Benefits of approach	Limitations of approach	Relevant literature
Travel cost	Direct and indirect use	Recreational use of planted forests	Based on observed behavior	Non-use value cannot be captured; limited to direct use values and recreational benefits; difficulties arise when trips are made to multiple destinations.	Turner et al. (2011)
Hedonic pricing	Direct and indirect use	Value of wood quality/attributes	Based on market data	Very data-intensive; difficulties arise when the market structure shift due to non-marginal environmental change.	Alzamora and Apiolaza (2010)
Contingent valuation	Use and non-use	Value of an afforestation or conservation program	Able to capture use and non-use values	Bias in survey design and sampling process due to the hypothetical nature of the market; resource-intensive method.	Yao and Kaval (2010)
Choice experiment	Use and non-use	Trade-offs among wood attributes	Able to capture use and non-use values. Able to measure the trade-offs among attributes and the marginal value of attributes	Similar to contingent valuation above, plus difficulties in choosing attributes and attribute levels.	Yao (2012)

and nutrient and water availability. According to Natural Resources Canada (2016), more frequent and longer lasting droughts are likely to induce changes in disturbance regimes, such as significantly increasing the annual burned forest area. The increasing atmospheric pollutants of particulates, nitrogen compounds, and ozone will also likely increase the intensity of insect outbreaks and disease problems (Evans 2009). For instance, warmer winters have already contributed to the major infestation of the mountain pine beetle in the province of British Columbia, Canada; the pine beetle has also spread over the Rocky Mountains into Alberta (Natural Resources Canada 2016). With the realization and acceptance that the climate is changing and that these changes will affect the forestry sector, applying tree improvement for planted forests could reduce the negative impacts of climate change through carbon sequestration and adaptation.

Planted forests can be used to sequester carbon and have the potential to relieve pressure on natural forest harvesting. With fast-growing trees selected by tree improvement programs, there is a greater potential for carbon sequestration by using the improved tree stock. Thus, investigating the economic effects of tree improvement as a management option for planted forests that addresses climate change is also an important part of the economic impact analysis process. In a case study in Argentina, Sedjo (1999) used a present-value approach to evaluate the costs and benefits of using improved seedling material for plantation forestry and found that the plantation investment can only be justified when the value of carbon sequestration is considered along with timber values. Therefore, results that do not consider the value of carbon sequestration may be misleading and lead to inefficient policy decisions. Yaron (2001) conducted a case study in tropical Africa and estimated the total economic value of alternative land uses in the Mount Cameroon region.[1] By comparing the total economic values of oil palm and rubber plantations, sustainable forest use, and subsistence-oriented agriculture, Yaron (2001) found that sustainable forestry produces the highest economic return, when the value of carbon stored by the forest is explicitly considered. However, when private investors make plantation investment decisions, the economic benefits of carbon sequestration are typically not considered, which may lead to socially inefficient scenarios. Thus, it is imperative that governments establish a proper carbon pricing policy or payment system to incentivize sustainable development and greenhouse gas reduction.

Another potential economic benefit provided by tree improvement programs is the use of improved seedlings for agroforestry, which is a farming method that combines crops, livestock, and trees to take advantage of complementarities. Agroforestry is considered an effective and low-cost method of sequestering atmospheric carbon into vegetation and soil pools. A recent study by Baah-Acheamfour et al. (2014) supports the potential of an agroforestry approach to increase soil carbon sequestration in central Alberta, Canada.

Planting improved pest- and disease-resistant tree species selected through tree improvement programs can also be part of climate change adaptation strategies and reduce potential losses caused by climate change-induced pests and disease disturbances. A recent worldwide survey on insect and disease resistance suggested that certain targeted resistance programs have had a substantial effect on improving the health of planted forests, especially for major commercial species (Yanchuk and Allard 2009). The main concern with the traditional breeding approach is that it is resource demanding and time consuming, and it may be less effective under a rapid climate change scenario (Yanchuk and Allard 2009). Marker-assisted selection has also been proposed as an effective approach to reduce the cost and timeline of the breeding process (Xu and Crouch 2008, El-Kassaby et al. 2012). Studies have demonstrated that when high mortality has occurred due to biotic or abiotic factors, genomic tools such as marker-assisted selection are preferable for estimating the future breeding potential (El-Kassaby et al. 2012). Future work should focus on quantifying the economic impacts of tree improvement programs that apply the new biotechnology (e.g., genomic technology) to address climate change challenges.

5.5 Uncertainty of Future Markets

The world is changing rapidly. What will the future look like and how does this affect forest tree improvement today? According to White et al. (2014), the forestry sector faces three future challenges: (1) changing economic conditions, such as new markets, new products and new patterns of forest ownership; (2) changing environmental

---

[1] Alternative land uses include: (1) direct use value, such as the value of crop production, plantation agriculture, and timber use; (2) indirect use value, such as carbon stored per hectare valued at internationally accepted rates; and (3) non-use value, such as value of knowing the existence of endangered species.

conditions, such as climate change, the rise of invasive species, and competition for land with agriculture to feed a growing population; and (3) new technologies. However, addressing these future uncertainties in an informed and objective manner is exceedingly difficult. The use of sensitivity analyses and stochastic modelling approaches are often used to obviate the need to make seemingly *ad hoc* decisions regarding specific parameters, but can sometimes lead to imprecise results. Nevertheless, it is important to recognize these challenges and develop a systematic approach that considers the entire system in order to encourage dialogue between tree breeders, natural/social scientists, and economists (Porth et al. 2015).

6 Conclusions and Recommendations

This paper conducted a systematic review and information gap analysis about the economic evaluations of tree improvement for planted forests. The main finding is that most of the studies we examined were conducted with the objective of wood production for commercial use and investigated from a forest manager's perspective. Studies have found that using improved reforestation stock for planted forests can realize financial benefits for tree growers and forest companies when compared with the use of unimproved material. Economic incentives for wood production are the main reason for forest managers to deploy new biotechnology in tree improvement for planted forests, although the paradigm is shifting to recognize the need for resilient, healthy forests rather than a simple focus on increasing the volume of wood produced. Cost-benefit analysis is the main economic application tool for examining the economic effects of tree improvement programs for planted forests. A sensitivity analysis and break-even approach should be conducted for program justification and to account for future uncertainties. Systematic literature searches have also found that the non-market trait values (e.g., carbon sequestration, watershed protection, or conservation values of genetic diversity) in tree improvement are gaining attention; however, these non-market trait values were usually not investigated in the past, as they do not depend on changes to the market traits targeted by tree breeders.

Compared to traditional breeding approaches, new biotechnology in tree breeding, such as genomics-assisted tree breeding, not only can effectively increase timber volume and improve wood quality traits but can also significantly reduce breeding cycles, leading to a shorter rotation period, and therefore reduce uncertainty. Thus, future economic evaluations of alternative tree improvement methods for planted forests should examine the benefits of time savings along with the consideration of research and overhead costs that may occur in the cost-benefit analysis framework. Moreover, future research should investigate the trade-offs between timber volume and wood quality traits; examine the economic effects of tree improvement from the different stages of production systems, i.e., from tree growers to wood processors; and assess how new biotechnology in tree improvement might affect downstream wood product markets (e.g., prices and international trade). In addition, the non-market values of breeding objective traits should be explicitly accounted for and estimated, using non-market valuation techniques, to ensure that the total economic values, including both market (financial) and non-market (social) values, of the tree improvement programs are captured. Economic analyses along these lines will help tree growers, private investors, and sawmill operators consider the trade-offs associated with alternative breeding objectives more comprehensively, thereby achieving more economically efficient investment decisions for planted forests.

7 References

Ahtikoski, A., and Pulkkinen, P. (2003). Cost-benefit analysis of using orchard or stand seed in Scots pine sowing, the case of northern Finland. *New Forests* 26, 247–262.

Ahtikoski, A., Ojansuu, R., Haapanen, M., Hynynen, J., and Kärkkäinen, K. (2012). Financial performance of using genetically improved regeneration material of Scots pine (*Pinus sylvestris* L.) in Finland. *New Forests* 43, 335–348.

Ahtikoski, A., Haapanen, M., Hynynen, J., Karhu, J., and Karkkainen, K. (2018). Genetically improved reforestation stock provides simultaneous benefits for growers and a sawmill, a case study in Finland. *Scandinavian Journal of Forest Research* 33, 484–492.

Alzamora, R., and Apiolaza, L. (2010). A hedonic approach to value *Pinus radiata* log traits for appearance-grade lumber production. *Forest Science* 56, 281–289.

Baah-Acheamfour, M., Carlyle, C.N., Bork, E.W., and Chang, S.X. (2014). Trees increase soil carbon and its stability in three agroforestry systems in central Alberta, Canada. *Forest Ecology and Management* 328, 131–139.

Costanza, R., D'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton P., and van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260.

El-Dien, O.G., Ratcliffe, B., Klápště, J., Porth, I., Chen, C., and El-Kassaby, Y.A. (2016). Implementation of the realized genomic relationship matrix to open-pollinated white spruce family testing for disentangling additive from non-additive genetic effects. *Genes, Genomes, Genetics* 6, 743–753.

Evans, J. (2009). The multiple roles of planted forests. Pages 61–90 in *Planted forests: Uses, Impacts and Sustainability*, ed. J. Evans. Food and Agriculture Organization of the United Nations (FAO) and CAB International, Rome.

El-Kassaby, Y., Klápště, J., and Guy, R. (2012). Breeding without breeding: selection using the genomic best linear unbiased predictor method (GBLUP). *New Forests* 43, 631–637.

Food and Agriculture Organization of the United Nations (FAO). (2015). *Global Forest Resources Assessment 2015* [online]. Rome, Italy. Available from http://www.uncclearn.org/sites/default/files/inventory/a-i4793e.pdf.

Food and Agriculture Organization of the United Nations (FAO). (2016). *Definitions-Planted Forests* [online]. Rome. Available from http://www.fao.org/forestry/plantedforests/67504/en/.

Frampton, J. (1996). The tree improvement process. *Limbs and Needles* 23, 10–14.

Grattapaglia, D., and Resende, M.D.V. (2011). Genomic selection in forest tree breeding. *Tree Genetics & Genomes* 7, 241–255.

Holmes, T., Adamowicz, W., and Carlsson, F. (2014). Chapter 5: Choice experiments. Pages 133–186 in *A Primer on the Economic Valuation of the Environment,* ed. P. Champ, T. Brown, and K. Boyle. Kluwer, Boston.

Isik, F. (2014). Genomic selection in forest tree breeding: the concept and an outlook to the future. *New Forests* 45, 379–401.

Ivković, M., Wu, H.X., McRae, T.A. and Powell, M.B. (2006a). Developing breeding objectives for radiata pine structural wood production. I. Bioeconomic model and economic weights. *Canadian Journal of Forest Research* 36, 2920–2931.

Ivković, M., Wu, H.X., McRae, T.A. and Matheson, A.C. (2006b). Developing breeding objectives for production of radiata pine structural wood. II. Sensitivity analyses. *Canadian Journal of Forest Research* 84, 2933–2943.

Ivković, M., Wu, H.X., and Kumar, S. (2010). Bio-economic modelling as a method for determining economic weights. *Silvae Genetica* 59, 77–90.

Jansson, G., Hansen, J.K., Haapannen, M., Kvaalen, H., and Steffenrem, A. (2017). The genetic and economic gains from forest tree breeding programs in Scandinavia and Finland. *Scandinavian Journal of Forest Research* 32, 273–286.

Jayawickrama, K.J.S. (2001). Genetic parameter estimates for radiata pine in New Zealand and New South Wales: a synthesis of results. *Silvae Genetica* 50, 45–53.

Kimberley, M.O., Moore, J.R., and Dungey, H.S. (2015). Quantification of realised genetic gain in radiate pine and its implication into growth and yield modelling systems. *Canadian Journal of Forest Research* 45, 1676–1687.

Kretschmann, D.E., and Bendtsen, B.A. (1992). Ultimate tensile stress and modulus of elasticity of fast-grown plantation loblolly pine lumber. *Wood and Fiber Science* 24, 189–203.

Lee, S., and Watt G. 2012. Improved Sitka spruce planting stock; seedlings from a clonal seed orchard or cuttings from full-sibling families? *Scottish Forestry* 66, 18–25.

McKeand, S.E., Abt, R.C., Allen, H.L., Li, B. and Catts, G.P. (2006). What are the best loblolly pine genotypes worth to landowners? *Journal of Forestry* 7, 352–358.

McKenney, D., van Vuuren, W., and Fox, G.C. (1989). An economic comparison of alternative tree improvement strategies-A simulation approach. *Canadian Journal of Agricultural Economics* 37, 211–232.

McKenney, D., Glenn, F., and van Vuuren, W. (1992). An economic comparison of black spruce and jack pine tree improvement. *Forest Ecology and Management* 50, 85–101.

McKenney, D. (2000). What's the economics of intensive silviculture? *Forestry Chronicle* 76, 275–281.

McKenney, D. (2001). Thinking about the economics of genetic resource management for Canadian forestry. *Forestry Chronicle* 77, 105–109.

Natural Resource Canada. (2016). Forest Carbon [online]. Available from https://www.nrcan.gc.ca/forests/climate-change/forest-carbon/13085.

Olesen I., Gjerde, B., and Groen, A. (1999). Methodology for deriving non-market trait values in animal breeding goals for sustainable production systems. *Proceedings International Workshop on EU Concerted Action on Genetic Improvement of Functional Traits in Cattle (GIFT): Breeding Goals and Selection Schemes, Wageningen, The Netherlands, 7–9th November 1999*. Available from http://library.wur.nl/WebQuery/wurpubs/62588.

Olesen I., Gjerde, B., and Groen, A. (2000). Definition of animal breeding goals for sustainable production systems. *Journal of Animal Science* 78, 570–582.

Palmer, H.E., Newton, A.C., Doyle, C.J., Thomson, S. and Stewart, L.E.D. (1998). An economic evaluation of alternative genetic improvement strategies for farm woodland trees. *Forestry* 71, 333–347.

Park, W-S., Weng, Y., and Mansfield, S.D. (2012). Genetic effects on wood quality traits of plantation-grown white spruce (*Picea glauca*) and their relationships with growth. *Tree Genetics & Genomes* 8, 303–311.

Paquette, A., and Messier, C. (2010). The role of plantations in managing the world's forests in the Anthropocene. *Frontiers in Ecology and the Environment* 8, 27–34.

Payn, T., Carnus, J-M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C., Rodriguez, L., Silva, L.N., and Wingfield, M.J. (2015). Changes in planted forests and future global implications. *Forest Ecology and Management* 352, 57–67.

Pearse, P.H. (1990). *Introduction to Forestry Economics*. University of British Columbia Press, Vancouver. 226 p.

Petrinovic, J.F., Gélinas, N., and Beaulieu, J. (2009). Benefits of using genetically improved white spruce in Quebec: The forest landowner's viewpoint. *Forestry Chronicle* 85, 571–582.

Poland, J.A., and Rife, T.W. (2012). Genotyping-by-sequencing for plant breeding and genetics. *Plant Genome* 5, 90–102.

Porth, I., Bull, G., Ahmed, S., El-Kassaby, Y.A., and Boyland, M. (2015). Forest genomics research and development in Canada: priorities for developing an economic framework. *Forestry Chronicle* 91, 60–70.

Porth, I., Bull, G., Cool, J., Gélinas, N., and Griess, V.C. (2016). An economic assessment of genomics research and development initiative projects in forestry. *CAB Reviews* 11, 1–10.

Ratcliffe, B., El-Dien, O.G., Klápště, J., Porth, I., Chen, C., Jaquish, B., and El-Kassaby, Y.A. (2015). A comparison of genomic selection models across time in interior spruce (Picea engelmannii x glauca) using unordered SNP imputation methods *Heredity* 115, 547–555.

Ratcliffe, B. El-Dien, O.G., Cappa, E.P., Porth, I., Klápste, J., Chen, C., and El-Kassaby, Y.A. (2017). Single-step BLUP with varying genotyping effort in open-pollinated *Picea glauca*. *G3: Genes, Genomes, Genetics* 7, 935–942.

Schreiber, S.G., and Thomas, B.R. (2017). Forest industry investment in tree improvement – a wise business decision or a bottomless pit? Answers from a new tree improvement valuation model for Alberta, Canada. *The Forestry Chronicle* 93, 38–43.

Sedjo, R.A., (1999). Potential for Carbon Forest Plantations in Marginal Timber Forests: The Case of Patagonia, Argentina. *RFF Discussion Paper 99-27*, Resources for the Future, Washington DC. 20 p.

Sedjo, R.A. (2001). Biotechnology in forestry: considering the costs and benefits. *Resources* 145, 10–12.

Sedjo, R.A. (2003). Biotech and planted trees: some economic and regulatory issues. *AgBioForum* 6, 113–119.

Simonsen, R., Rosvall, O., Gong, P., and Wibe, S. (2010). Profitability of measures to increase forest growth. *Forest Policy and Economics* 12, 473–482.

Simonsen, R. (2013). Optimal regeneration method-planting vs. natural regeneration of Scots pine in northern Sweden. *Silva Fennica 47*, article id 928. 23 p.

Thomas, B.R., and Richardson, J. (2006). Poplar genomics to poplar production: Bridging the gap for best use of our resources and knowledge. Report prepared for Genome Canada [online]. Available from http://www.poplar.ca/upload/documents/g2ppaper.pdf.

Tong, A., Palmer, S., Craig, J.C., and Strippoli, G.F.M. (2016). A guide to reading and using systematic reviews of qualitative research. *Nephrology Dialysis Transplantation* 31, 897–903.

Turner, J.A., Dhakal, B., Yao, R., Barnardl, T., and Maunder, C. (2011). Non-timber values from planted forests: Recreation in Whakarewarewa Forest. *New Zealand Journal of Forestry Science* 55, 24–31.

Vossler, C.A, Doyon, M., and Rondeau, D. (2012). Truth in consequentiality: theory and field evidence on discrete choice experiments. *American Economic Journal: Microeconomics* 4, 145–171.

White, T., Davis, J., Gezan, S., Hulcr, J., Jokela, E., Kirst, M., Martin, T.A., Peter, G., Powell, G., and Smith, J. (2014). Breeding for value in a changing world: past achievements and future prospects. *New Forests* 45, 301–309.

Wu, H.X., Yang, J.L., Mcrae, T.A., Li, L., and Powell, M.B. (2004). *Genetic relationship between breeding objective and early selection criterion traits in Australia radiata pine population*. CSIRO CFFP Technical Report 1402 and STBA Technical Report TR04-01. CSIRO, Canberra.

Wu, H.X., Eldridge, K.G., Matheson, A.C., Powell, M.B., McRae, T.A., Butcher, T.B., and Johnson, I.G. (2007). Achievements in forest tree improvement in Australia and New Zealand 8. Successful introduction and breeding of radiata pine in Australia. *Australian Forestry* 70, 215–225.

Wu, Y.Q., Weng, Y.H., Hennigar, C., Fullarton, M.S., and Lantz, V. (2015). Benefit-cost analysis of a white spruce clonal seed orchard in New Brunswick, Canada. *New Forests* 46, 141–156.

Xu, Y., and Crouch, J.H. (2008). Marker-assisted selection in plant breeding: from publications to practice. *Crop Science* 48, 391–407.

Yanchuk, A., and Allard, G. (2009). Tree Improvement Programs for Forest Health – Can They Keep Pace with Climate Changes? *Unasylva* 60 (231/232) [online]. Available from http://www.fao.org/3/i0670e11.htm.

Yao, R. and Kaval, P. (2010). Valuing biodiversity enhancement in New Zealand. *International Journal of Ecological Economics and Statistics* 16, 26–42.

Yao, R. (2012). *The Non-Market Value of Biodiversity Enhancement in New Zealand's Planted Forests*. Ph.D. Dissertation. University of Waikato, Hamilton, New Zealand. Available from http://hdl.handle.net/10289/6399.

Yaron, G. (2001). Forest, plantation crops or small-scale agriculture? An economic analysis of alternative land use options in the mount Cameroon area. *Journal of Environmental Planning and Management* 44, 85–108.

Zobel, B.J., and Talbert, B.J. (1984). *Applied Tree Improvement*. Wiley, New York. 448 p.