TRADE-OFFS BETWEEN ECONOMIC GAINS AND ECOLOGICAL FUNCTIONS FOLLOWING FOREST MANAGEMENT ALTERNATIVES IN BOREAL FORESTS

By

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ABSTRACT

Intensive forest management activities that maximize economic gains could negatively impact the long-term sustainability of ecological functions and associated ecosystem services. Understanding the trade-offs between economic gains and ecological losses is critical for sustainable management of forest resources. However, the effects of management alternatives on ecological functions and services have not been thoroughly investigated. The objective of this dissertation is to improve the understanding of trade-offs and synergies between economic gains and ecological functions in the boreal forest ecosystem. To achieve this goal, I first conducted a global review of economic and ecological trade-off analysis of forest ecosystems in chapter 2, demonstrated the principal analytical economic and ecological trade-off methods, and found that economic and ecological trade-offs remained poorly understood with limited ecological functions and ecosystem services following forest management alternatives in boreal forests.

In chapter 3, in order to help decision makers select the economically optimal forest management alternatives, I examined the impact of forest management alternatives on economic gains, assessed as profit. I found that silvicultural intensity, forest composition, rotation age, and harvest method significantly affected profit. The results indicated that profit was higher when low silvicultural intensity (conifer – conifer) and Full-Tree to Roadside Tree-Length-to-Mill harvesting method (FT-TL) were applied with a rotation age of 100 years.

Inspired by the conclusion of the global review, I chose two important ecological functions, plant diversity (habitat function) and carbon (C) stocks (regulation function), to evaluate their relationship with economic gains following forest management alternatives (managing rotation age and overstorey composition) in chapters 4 and 5, respectively. I found that forest management alternatives as major drivers determining profit, and plant diversity and C stocks. In the economic gain-plant diversity relationship study, I found hump-shaped trade-off relationships between profit and plant diversity following forest management alternatives, both for total species richness and richness of individual forest strata (shrub, understorey vascular and non-vascular species strata), except for a positive linear relationship between profit and overstorey diversity. Among the alternatives, I concluded that managing for mixedwood with approximately a rotation of 100 years is an optimal compromise between economic gain and plant diversity objectives.

In the economic gain-C stock relationship study, I also found hump-shaped relationships between profit and C stocks of total ecosystem and individual pools (total live biomass, total deadwood, forest floor and mineral soil). When analyzed by overstorey composition, the relationships between profit and total deadwood C and mineral soil C were synergic across a wide range of profits in coniferous stands, while those were initially synergic and became trade-off with increasing profit in broadleaved and mixedwood stands. Among the alternatives, I further concluded that managing for coniferous stands with approximately a rotation of 100 years is an optimal management option that optimizes both economic gain and C stocks objectives.

The results showed that the relationships between economic gains and ecological functions are predominantly non-linear in boreal forests. These results will help forest managers and decision-makers in defining optimum management options with limited or no ecological losses while satisfying economic gains.

Key-words: boreal forest, carbon stocks, carbon pools, ecological functions, economic analysis, economic gains, ecosystem services, forest management alternatives, harvest method, overstorey composition, plant diversity, rotation age, silvicultural intensity, synergies, trade-offs, vegetation strata

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CHAPTER 1: GENERAL INTRODUCTION

Human society is inextricably linked to forest ecosystems, which provide a wide variety of functions and services that are of increasing values for economic, ecological, and social objectives (Millennium Ecosystem Assessment 2005). These include production functions and provisioning services (e.g., economic gains from food, fibre, and raw materials), habitat functions and supporting services (e.g., maintaining biodiversity, soil formation, photosynthesis, and pollination), regulation functions and regulating services (e.g., climate regulation, disease control, and water filtration), and information functions and cultural services (e.g., spiritual, aesthetic, and recreational values) (de Groot et al. 2002, Millennium Ecosystem Assessment 2005). As one of the world's most important bio-geoclimatic areas (Bradshaw et al. 2009, Brandt 2009), boreal forests account for 30% of global terrestrial phytomass and constitute approximately 45% of the global growing stock of timber with economic gains as important forestry objectives (Vanhanen et al. 2012). In order to produce a range of value-added forest products, a number of forest management alternatives have been applied to the boreal forests, involving compositional objectives, rotation ages, and harvest methods. However, intensive forest management that maximizes economic gains could lead to the impairment or degradation of long-term ecological functions, and in turn cascade into the poor delivery of ecosystems services (Costanza et al. 2014). The economic and ecological trade-offs are often highly nonlinear (Chan et al. 2006, Steffan-Dewenter et al. 2007), and revealed conflicting results of trade-offs, synergies or no effect. It remains uncertain how economic activities might best maintain and support multiple ecological functions and services in boreal forests. Understanding the trade-offs or synergies between economic gains and ecological functions is critical for the sustainable forest management (Frank and Schlenker 2016).

The objective of this dissertation is to fill the knowledge gap of the trade-offs and synergies between economic gains and ecological functions following forest management alternatives in boreal forests. To achieve this goal, I first conducted a global review of economic and ecological trade-off analysis of forest ecosystems in chapter 2. I found that economic and ecological trade-offs are poorly understood in boreal forests with limited ecological functions and ecosystem services. Then, I conducted an empirical economic analysis of forest management alternatives in boreal forests in chapter 3. Finally, I chose two important ecological functions, plant diversity (habitat function) and C stocks (regulation function), and evaluated their relationships with economic gains across vegetation strata following forest management alternatives in boreal forests in chapter 4 and 5, respectively.

Chapters 2 and 3 of this dissertation have already been published (Chapter 2 in *Environmental Reviews* (Chen et al. 2016b)) and Chapter 3 in *Forest Policy and Economics* (Chen et al. 2017)). Chapter 4 is currently under revision in *Ecological Economics*, and Chapter 5 is under review in *Forest Policy and Economics*. Since each chapter has been written individually according to publication requirements, I have made reference to Chapter 2 in Chapters 3, 4, and 5; and Chapter 3 in Chapters 4 and 5, respectively. Also, since individual chapters reflect joint contributions from myself and my academic supervisors, I presented ―we” instead of ―I’ as written for individual manuscripts.

CHAPTER 2: ECONOMIC AND ECOLOGICAL TRADE-OFF ANALYSIS OF FOREST ECOSYSTEM: OPTIONS FOR BOREAL FORESTS

2.1 Abstract

Intensive forest management practices for production forestry can potentially impact the sustainability of ecological functions and associated forest ecosystem services. Understanding the trade-offs between economic gains and ecological losses is critical for the sustainable management of forest resources. However, economic and ecological trade-offs are typically uncertain, vary at temporal and spatial scales, and are difficult to measure. Moreover, the methods used to quantify economic and ecological trade-offs might have conflicting priorities. We reviewed the most current published literature related to trade-off analysis between economic gains and sustainability of forest ecosystem functions and associated services and found that most economic and ecological trade-offs studies were conducted in tropical and temperate forests, with few having their focus on boreal forests. Analytical methods of these published studies included monetary valuation, biophysical models, optimization programming, production possibility frontier and multi-objective optimization. This review has identified the knowledge gaps in the understanding and measurement of the economic and ecological trade-offs for the sustainable management of boreal forests. While it remains uncertain how economic activities might best maintain and support multiple ecological functions and associated services in the boreal forests, which are susceptible to climate change and disturbances, we propose the use of optimization methods employing

multiple objectives. For any tool to provide sustainable and optimal forest management solutions, we propose that appropriate and robust data must be collected and analyzed.

2.2 Introduction

Human society is inextricably linked to forest ecosystems, which provide an extensive array of functions and services that are of increasing value for societal and economic prosperity (Millennium Ecosystem Assessment 2005). Ecological functions include any natural processes that control energy flux, nutrients, and organic matter within forest ecosystems (Cardinale et al. 2012). These ecological functions provide four primary categories of ecosystem services to humanity, which include: (i) production functions and provisioning services (e.g., renewable raw materials such as timber, fiber, pharmaceuticals, food, bioenergy, and non-renewable energy resources), (ii) habitat functions and supporting services (e.g., supporting biodiversity, nutrient cycling, and primary productivity), (iii) regulation functions and regulating services (e.g., pollination, climate regulation, and carbon sequestration), and (iv) information functions and cultural services (e.g., recreational and aesthetic values) (de Groot et al. 2002, Millennium Ecosystem Assessment 2005). The overall value of forest ecosystems encompasses both extractive/priceable services, and non-extractive/unpriceable services (Zhang and Pearse 2012). However, the economic gains garnered from forest ecosystems are only provided through production functions and provisioning services, which may be exchanged for currency in the markets. With increasing anthropogenic pressures that impinge on forests, intensive forest management practices that aim to maximize economic gains have impacted the sustainability of forest ecosystems and their ecological processes (Vitousek 1997, Costanza et al. 2014).

The valuation of ecological functions and services of forest ecosystems is a difficult and controversial task, where economists have often been criticized for attempting to affix a price tag on nature (Heal 2000, Admiraal et al. 2013, Adams 2014). However, the trade-offs in the allocation of resources to protect forest ecosystems might only be understood through economic decisions that are based on societal values. The perceptions of ecologists may be completely different due to ineffective policies or institutions (Femia et al. 2001). Under the imbalanced provision of economic and ecological forest ecosystem valuation, the cost of ecological losses through interventions into natural processes is the price that society must pay in return for the economic gains (Rodriguez et al. 2006). For example, the production of industrial grade wood from the boreal forests of Canada has led to the degradation of ecological functions and services in boreal zones (Brandt et al. 2013). Economic and ecological trade-offs are typically uncertain and difficult to reconcile with an increasing emphasis on intensive forest management across a wide range of temporal and spatial scales (Rodriguez et al. 2006). Therefore, there is a need to explore the trade-offs between suitable options for intensive forest management that may satisfy economic gains, while simultaneously minimizing losses in ecological functions and associated services from forest ecosystems (DeFries et al. 2004, Steffan-Dewenter et al. 2007).

In the boreal forests of Canada, forest management practices are prescribed to efficiently and effectively maintain and enhance the long-term health of forest ecosystems (Burton et al. 2006). For example, the two principles under the Crown Forest Sustainability Act (CFSA, 1994) that assist in sustainably managing forests to meet the environmental, economic, and social requirements for present and future generations include: (i) conservation of ecological functions and biological diversity, and (ii) emulating natural disturbances, while minimizing adverse impacts on forest valuation. In order to safeguard these two principles, the response of a forest ecosystem to forest management practices (primarily harvesting) must be quantified in order to ensure that species diversity, population trends, community organization, and functional properties are in alignment with typical responses to natural disturbances (e.g., fires, drought, severe storms, and insect attacks) (Attiwill 1994, Landres et al. 1999, Parkins and MacKendrick 2007, Venier et al. 2014). Forest management options for Canadian boreal forests include two primary biomass harvesting methods; stem-only harvesting for sawlogs and pulp logs, and full-tree harvesting for maximizing biomass extraction from the forests, which may have detrimental effects in terms of the sustainability of ecological functions and associated services (Canadian Council of Forest Ministers 2005, Maynard et al. 2014). However, our understanding of the economic and ecological trade-offs of these forest management practices remain limited.

An improved understanding of the trade-offs between economic gains and ecological functions at various spatial and temporal scales may assist in decision-making, and strengthening policy formulation, for forest management practices that incorporate multiple objectives (Nelson et al. 2009, McShane et al. 2011). However, to the best of our knowledge, there is no systematic review that provides a comprehensive picture of economic and ecological trade-off studies across the globe, or the methods used thereof, for arriving at these trade-off comparisons in forest ecosystems. This knowledge gap impedes the ability of forest managers and researchers to evaluate the consequences of different forest management scenarios. Trade-off analysis will facilitate the identification of optimum forest management options with efficient resource-use and renewal patterns that maximize economic gains while minimizing ecological losses. Therefore, the rationale behind this paper was to review the published literature over the last twenty years that sought to measure and explain the economic and ecological trade-offs of forest management options with conflicting priorities. Specifically, our objectives were: (i) to assess the current state of economic and ecological trade-off studies that have been conducted in forest ecosystems, (ii) to examine and classify the methods used in these studies, and (iii) to explore suitable options for forest management under conflicting priorities in boreal forests.

2.3 Approach

2.3.1 Definition of terms

In this review, economic gains are defined as the profits or discounted constant dollar values from total or partial outputs of merchantable forest resource extraction. Economic gains should be quantified in monetary units, coming mainly from production functions and provisioning services, such as timber and non-timber products that could be exchanged in the markets. In contrast, ecological losses include a wide range of ecological functions and services provided by forest ecosystems that cannot be exchanged in the markets.

2.3.2 Literature selection

The online search engine, Thomson Reuters (ISI) Web of Knowledge (2016), was employed to search published (1994 – 2016) peer-reviewed economic and ecological trade-off journal articles. Different combinations of search terms and keywords, such as –economic gain”, –economic benefit”, –economic development”, “economic return”, –ecological function”, –ecosystem service”, –trade*”, and –trade-off”, were employed to ensure that the searches included all relevant economic and ecological trade-off studies of forest ecosystems. The literature cited by the retrieved articles were also consulted in order to seek additional relevant articles. From the search, we extracted 101 original journal articles that focused on economic and ecological trade-off analyses in forest ecosystems. Subsequently, the selected peer-reviewed articles were examined in depth to investigate the methods used for economic and ecological trade-off comparisons, and the eligible peer-reviewed articles were categorized based on these methods.

2.4 Current state of trade-off studies

The spatial distribution of the studies, using economic and ecological comparison methods, encompassed an extensive global reach (Figure 2.1), albeit there was a notable absence of such studies in Northern Eurasia, the Middle East, and Africa. Worldwide, economic and ecological trade-off studies were heavily skewed toward tropical and temperate forests, accounting for 74.3% of the peer-reviewed articles, whereas only 25.7% of the articles investigated boreal forests. The top three countries included the United States (27 articles), Finland (12 articles), and Indonesia (8 articles), which represented nearly half of the total peer-reviewed articles. Moreover, the majority of the economic and ecological comparison studies focused on biodiversity and habitat diversity (42.9%). Additional ecological functions and ecosystem services in the studies encompassed carbon stocks and sequestration (29.2%), water regulation and supply (7.1%), cultural services (6.5%), erosion protection and soil fertility (5.8%), disturbance regulation (2.6%), pollination services (2.6%), waste regulation (1.3%), oxygen production (1.3%), and surface albedo (0.7%) (Figure 2.2).

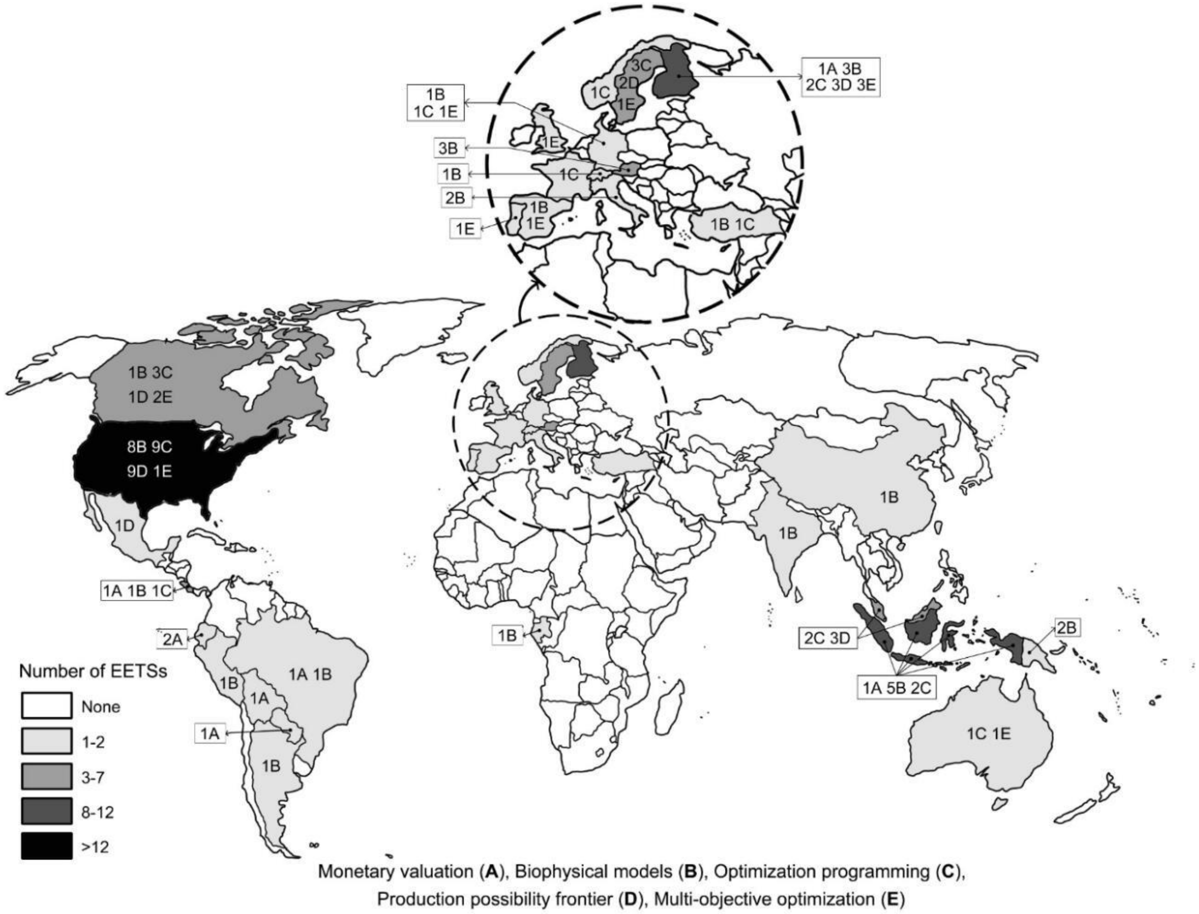

Figure 2.1. Geographical distribution of economic and ecological trade-off studies (EETSs).

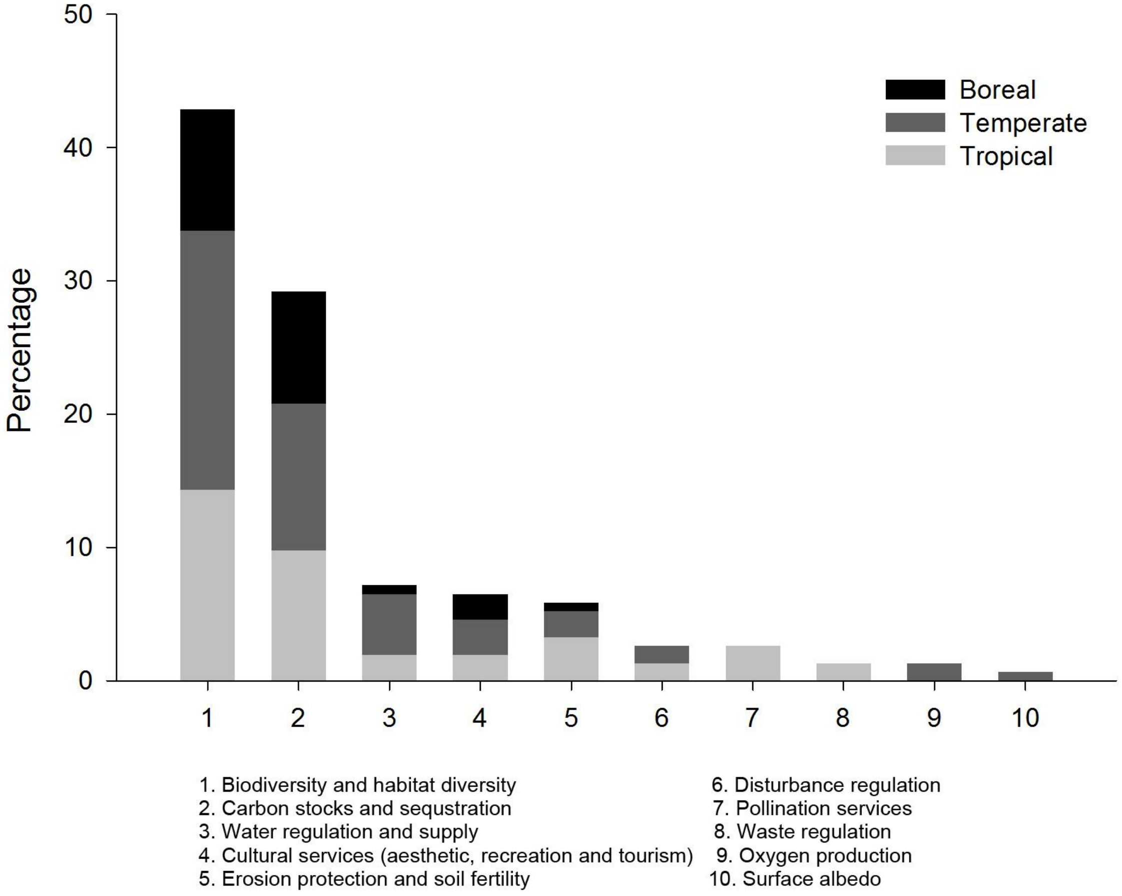

Figure 2.2. Percentage of ecological functions and ecosystem services involved in the economic and ecological trade-off studies.

2.5 Economic and ecological trade-off methods

Based on the methods classification criteria, both monetary and non-monetary techniques were employed for economic and ecological trade-off methods. Monetary valuation methods analyze trade-offs by comparing economic gains with ecological goals as net present values based on cost-benefit evaluations. Monetary valuation methods have been commonly employed for tropical agroforests, with only a single study found for boreal forests (Ahtikoski et al. 2011). However, non-monetary modeling techniques for ecological losses (92.1% of the studies) formed the majority of trade-off methods, including biophysical models (37.6%) and operations research models (62.4%); a modeling technique that utilizes advanced analytical optimization to facilitate improved decisions. Three categories of operations research models have been commonly used for trade-off analyses, including optimization programming (46.6%), production possibility frontier (32.7%), and multi-objective optimization (20.7%) (Winston and Goldberg 2004) (Figure 2.3).

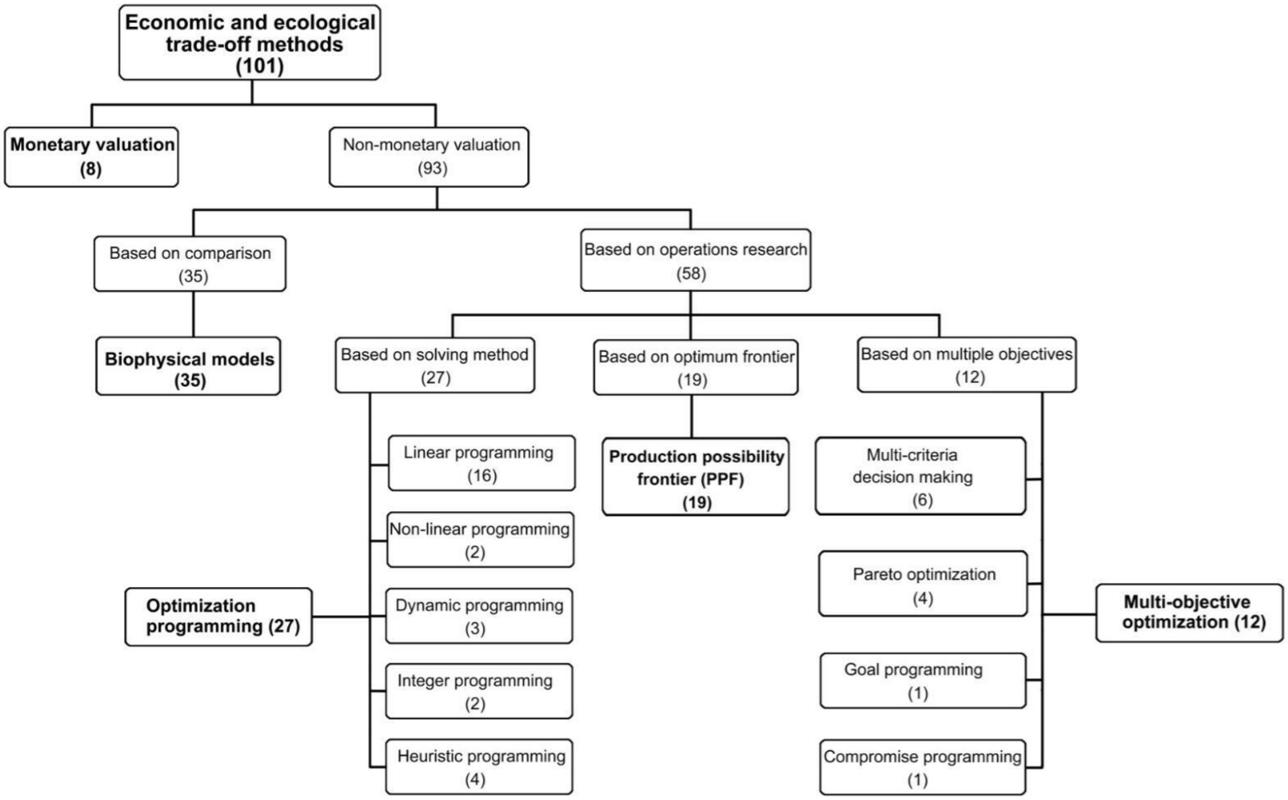

Figure 2.3. Classification of primary economic and ecological trade-off methods.

2.5.1 Monetary valuation

Monetary valuation is an interdisciplinary collaboration, where economists attempt to evaluate the dollar value of ecological functions and ecosystem services, which are otherwise unpriced in the market (Farley 2008). A wide range of calibration tools have been developed for monetary valuation, which may be divided into the following three categories (Gatto and De Leo 2000, Farber et al. 2006, Turner et al. 2016): (i) replacement and restoration costs that use market prices of man-made treatment systems to replace or restore the impacted ecological functions and ecosystem services; (ii) stated preference methods (i.e., contingent valuation method), which attempts to build pseudo markets through hypothetical choices that ask consumers to state their willingness to pay for ecological functions and ecosystem services, which are not traded in markets; (iii) revealed preference methods that are used to evaluate market values for ecological functions and ecosystem services based upon the behaviors or attitudes of consumers, including travel cost methods and hedonic price methods. The price or marginal cost (i.e., change in total cost created by one unit increase in quantity) of ecological functions and ecosystem services is measured in order to understand the trade-offs between economic gains and tree species diversity (Bottazzi et al. 2014), carbon stock and sequestration (Naidoo and Ricketts 2006, Olschewski and Benitez 2010, Olschewski et al. 2010, Bottazzi et al. 2014), pollination services (Ricketts et al. 2004, Viglizzo and Frank 2006, Priess et al. 2007, Olschewski et al. 2010), cultural services (Ahtikoski et al. 2011), biological control, erosion control, soil formation, water regulation, waste treatment, gas regulation, and climate regulation (Viglizzo and Frank 2006). For example, Viglizzo and Frank (2006) analyzed the economic and ecological trade-offs by synthesizing more than 100 studies that priced ecosystem services using a variety of monetary valuation methods across the globe (Costanza et al. 1997).

The application of monetary valuations enables the formulation of efficient policies for forest management that have the greatest social welfare (Godoy et al. 2000, Heal 2000, de Groot et al. 2012). Nevertheless, monetary valuations assigned to ecological functions and ecosystem services should be treated with caution for several reasons (Bateman et al. 2013). Firstly, monetary methods for pricing ecological functions and ecosystem services are unavoidably uncertain (Balmford et al. 2002), resulting in dissimilar valuations contingent on various stakeholders (Howe et al. 2014). Hence, diverse societies and evaluators with specific sociocultural preferences, in different environments and during different time periods, may result in different appraisals of ecological functions and ecosystem services (Martin-Lopez et al. 2012). For instance, willingness to pay is determined by preferences that are weighted by income and regional scarcity (Farley 2008, Wainger and Mazzotta 2011). Hence, forests may be highly valued by a wealthy population for their aesthetic and recreational attributes, in contrast to the financially challenged, who depend on the same forest resources for their subsistence. Secondly, not all ecological functions and ecosystem services may be measured directly or manipulated experimentally, and their economic values are not exclusive due to interactions and interdependence. In general, diverse components of ecological functions and ecosystem services are co-produced as bundles, which may interact synergistically or competitively (Bennett et al. 2009, Raudsepp-Hearne et al. 2010), and the relationships are likely to be highly nonlinear, resulting in unintentional economic trade-offs (Rodriguez et al. 2006).

Despite their problems, forest policies and incentives are established through monetary trade-off analyses. The policy of payments for ecosystem services (PES) is an example (Ricketts et al. 2004, Viglizzo and Frank 2006, Olschewski et al. 2010), which serves as a critical tool for the conservation and sustainability of forest resources, and improvement of human well-being (Ferraro and Kiss 2002, Wunder 2008, Redford and Adams 2009). This involves the users of ecological functions and ecosystem services; paying those who supply them through government programmes or private sector initiatives, as a tax or user fee. PES assists consumers to intuitively understand the importance of, and be rewarded for, the protection of forest ecosystems, while governments formulate appropriate policies. However, PES is not always the correct approach for every situation, as it sometimes fails to meet the criteria of actual markets, additional taxes, regulations, and zoning laws that are required to underpin the payment scheme (Muradian et al. 2013).

Therefore, it is challenging to develop standard and widely acceptable money-metric measures for unpriced ecological functions and ecosystem services (de Groot et al. 2012, Adams 2014). Monetary valuation is better suited for managed forest ecosystems with similar site conditions, such as agroforestry ecosystems, which are closely linked with the economic interests of individuals, along with easy market access. As managed forests are intended to be utilized for harvesting, some ecological services are better evaluated by the market price of replacement and restoration costs of forests, post-harvest. However, monetary measures are difficult to apply to natural forests that are not closely linked with socioeconomic value.

2.5.2 Biophysical models

Considering that intangible ecological services are difficult to be monetized in isolation, as these typically occur over different spatial and temporal scales, an understanding of the role of biophysical factors (such as light, slope, water conditions, soil texture and nutrients, climate, temperature, precipitation, humidity, and altitude) are crucial in explaining ecosystem components and processes for their future impacts (Redford and Adams 2009). Without appropriate modeling with biophysical factors, forest management policies, incentives or payment schemes that optimize the delivery of those services appear inefficient

(Nelson et al. 2009). Biophysical models may facilitate the analysis of trade-offs imbalance due to the application of land-use policies (Carreno et al. 2012), and often incorporate simulated trade-off scenarios of measurable economic gains (Nelson et al. 2009, Polasky et al. 2011, Goldstein et al. 2012). Ecological losses in the biophysical models are expressed in monetary, proportional, quantitative, or relative units.

Biophysical models have been commonly employed to study economic and ecological trade-offs in tropical and temperate forests, for both managed and unmanaged scenarios, with disturbances and natural cycles, without management intervention (Duncker et al. 2012b). In the reviewed literature, 45.7% of the studies that used biophysical models were conducted in tropical forests, primarily in agroforestry (Steffan-Dewenter et al. 2007, van Noordwijk et al. 2008, Clough et al. 2011, Goldstein et al. 2012, Mulia et al. 2014, Yi et al. 2014), and 42.9% in temperate forests, while there were only 11.4% in boreal forests. Biophysical models focus on balancing economic gains with biodiversity preservation (Hansen et al. 1995, Grasso 1998, Faith et al. 2001, Faith and Walker 2002, Marzluff et al. 2002, van Noordwijk 2002, Williams et al. 2003, Chopra and Kumar 2004, Steffan-Dewenter et al. 2007, Nelson et al. 2009, Prato 2009, Mendenhall et al. 2011, Polasky et al. 2011, Carreno et al. 2012, Duncker et al. 2012b, Gret-Regamey et al. 2013, Yi et al. 2014, Wood et al. 2016), carbon stocks or sequestration (Pussinen et al. 2002, van Noordwijk 2002, Garcia-Gonzalo et al. 2007, Seidl et al. 2007, Seidl et al. 2008, van Noordwijk et al. 2008, Nelson et al. 2009, Raudsepp-Hearne et al. 2010, Baskent et al. 2011, Duncker et al. 2012b, Goldstein et al. 2012, Gret-Regamey et al. 2013, Cademus et al. 2014, Mulia et al. 2014, Pyorala et al. 2014, Lutz et al. 2015, Bottalico et al. 2016), water regulation and supply (Nelson et al. 2009, Baskent et al. 2011, Carreno et al. 2012, Duncker et al. 2012b, Goldstein et al. 2012, Vidal-Legaz et al. 2013, Cademus et al.

2014, Gissi et al. 2016), erosion protection and soil fertility (Steffan-Dewenter et al. 2007, Nelson et al. 2009, Raudsepp-Hearne et al. 2010, Carreno et al. 2012, Gissi et al. 2016, Wood et al. 2016), cultural services (Raudsepp-Hearne et al. 2010, Gret-Regamey et al. 2013), disturbance regulation (Gret-Regamey et al. 2013, Maroschek et al. 2015), oxygen production (Baskent et al. 2011), and surface albedo (Lutz et al. 2015).

Although biophysical models may assist with the design of appropriate forest management strategies among alternative scenarios, a major limitation of these models is associated with the uncertainty of the true value of the model parameters (Vidal-Legaz et al. 2013). The factors and variables used in the generalized biophysical models are built mainly on the assumptions of metadata and ecological theories, and are lacking in empirical evidence due to the non-availability of data (Nelson et al. 2009). Biophysical models typically use simplified equations with fewer factors, which are relatively easy to measure (Carreno et al. 2012), to reduce the risk of multi-collinearity and auto-correlation among biophysical variables. This is because it is very difficult to quantitatively assess all interdependent biophysical factors (Bennett et al. 2009), and the model ignores many factors that may contribute to trade-offs (Holling and Meffe 1996, Adams 2014). Moreover, the trade-off analysis in biophysical models is derived from various units (e.g., monetary, proportional, quantitative, or relative), making it problematic to compare outcomes. The biophysical models, although superior to the monetary method, in both estimation scope and forecasting scale, suffer from the above-mentioned constraints.

2.5.3 Optimization programming

Unlike biophysical models that offer preferred solutions among diverse scenarios, optimization programming optimizes benefits from both economic and ecological perspectives. A series of analytical problem-solving optimality techniques have been adapted from the field of operations research to study economic and ecological trade-offs for forest ecosystems. Optimization programming methods assist with solving complex trade-off optimization problems constrained within diverse environments to arrive at optimal, or near-optimal, solutions for decision making, where one objective is optimized, and other objectives are treated as constraints (Winston and Goldberg 2004). Both economic and ecological objectives are measured through mathematical algorithms such as linear, non-linear, dynamic, integer, and heuristic programming. Linear programming, the most common and traditional optimization technique, aims to achieve optimum trade-off solutions through mathematical models with linear objective functions, governed by linear constrains (Hiroshima 2004). For example, linear programming was employed to examine the economic-ecological trade-offs that aim at maximizing objectives that are directly related to biodiversity, vegetative, or structural diversity (Holland et al. 1994, Buongiorno et al. 1995, Ingram and Buongiorno 1996, Boscolo and Buongiorno 1997, Onal 1997, Lin and Buongiorno 1998, Mendoza et al. 2000, Juutinen and Monkkonen 2007, McCarney et al. 2008), carbon stocks or sequestration (Hoen and Solberg 1994, Boscolo and Buongiorno 1997, Krcmar et al. 2001, Backeus et al. 2005, 2006, Baskent et al. 2008, McCarney et al. 2008, Zubizarreta-Gerendiain et al. 2016), biophysical sustainability, such as soil nutrient (Bouman et al. 1998), and oxygen production (Baskent et al. 2008). However, many real-world ecological and economic problems involve complex non-linear objective functions and constraints that cannot be specified by linear programming techniques. As a result, non-linear programming methods have also been utilized to develop forest management plans between monetary returns and the maintenance of tree size and structural diversity (Buongiorno et al. 1994, Kant 2002).

Dynamic programming is utilized by initially breaking the problem down into multiple time steps and simpler sub-problems that describe a sequential process, and then integrating the sub-solutions together to attain a precise solution (Stirn 2006). For example, dynamic programming methods provide an optimal balance with the quantification of trade-offs between economic gains, biodiversity conservation or carbon sequestration for a series of time steps in a multi-stage decision-making process (Doherty et al. 1999, Spring et al. 2005, Yousefpour and Hanewinkel 2009). Similarly, mixed integer programming, an optimization approach in which some or all variables are restricted to be integers (Wolsey 1998), has been used to incorporate an optimal balance between economic revenue and biodiversity (Rose and Chapman 2003, Ohman et al. 2011). Nevertheless, it is cumbersome to solve large trade-off problems with many integer variables and alternatives by considering all possible combinations of integer variables using mixed integer programming (Arthaud and Rose 1996), and for very complex economic-ecological trade-off problems, an exhaustive search is sometimes impractical due to the size of the problem. Heuristic programming then offers a set of approximations and global optimal solutions, rather than an exact solution (Murray and Church 1995). Heuristic programming has illustrated satisfactory solutions in trade-off analyses between economic timber harvests and wildlife conservation goals (Bettinger et al. 1997, Bettinger et al. 1998, Bettinger et al. 1999, Bettinger et al. 2003). However, the main drawback of heuristics is that they cannot guarantee optimality, and it is difficult to evaluate the suitability of an approximate solution (Nalle et al. 2004).

Although optimization programming methods may be used to develop optimal management plans ranging from small to large scale, these methods lack the ability to examine trade-offs among multiple objectives simultaneously. The non-availability of data coupled with the complexity of the market and environmental constraints have restricted the use of mathematical models that incorporate optimization programming. In addition, optimization programming methods focus on the selection of an exact solution, or an approximate global solution, thereby ignoring the opportunity to realize a series of indifferent optimum solutions with different objectives.

2.5.4 Production possibility frontier

The production possibility frontier (PPF) method employs a simulation-based optimization approach to arrive at a series of optimum management solutions. PPF is a graphic integration of optimization techniques that typically illustrates the trade-offs for two opposing objectives through an efficiency frontier, which is a state of resource allocation where it is not possible to make one objective better off without making another objective worse off (Calkin et al. 2002). The efficiency frontier indicates the cost-effective combinations of the two objectives with efficient (on the frontier), inefficient (below the frontier), and infeasible (above the frontier) solutions. The slope of the PPF is the marginal opportunity cost of the attainment of one objective at the expense of another (Lichtenstein and Montgomery 2003). In PPF, economic models are used to assess economic gains, whereas biophysical models, optimization programming, or monetary valuation methods are used to assess losses of ecological functions and associated services. For instance, PPF integrates heuristic programming to trace out an efficient trade-off frontier between economic and biodiversity objectives with a set of approximate solutions (Calkin et al. 2002, Lichtenstein and Montgomery 2003, Nalle et al. 2004, Polasky et al. 2005, Tikkanen et al. 2007, Polasky et al. 2008).

The production possibility frontier has been used to compare the trade-offs between timber values and biodiversity, specifically faunal diversity in tropical and temperate forests (Montgomery et al. 1994, Montgomery 1995, Arthaud and Rose 1996, Boscolo et al. 1997, Boscolo and Buongiorno 2000, Rohweder et al. 2000, Calkin et al. 2002, Boscolo and Vincent 2003, Lichtenstein and Montgomery 2003, Nalle et al. 2004, Perfecto et al. 2005, Polasky et al. 2005, Polasky et al. 2008), and timber values and carbon objectives in tropical forests (Boscolo et al. 1997, Boscolo and Buongiorno 2000, Boscolo and Vincent 2003). For example, Polasky et al. (2008) analyzed trade-offs of the biological and economic consequences of alternative forest management at a landscape level by developing a spatially explicit biological model, which incorporated habitat preferences, area requirements, and the dispersal ability for terrestrial vertebrate species, and a spatially explicit economic model, which integrated site characteristics and locations for economic prediction. Incorporating a heuristic approach, PPF identified efficient forest management alternatives that maximized biodiversity conservation for given levels of economic returns on the production set of feasible combinations, and vice versa. Only six PPF studies have been conducted in the boreal forests (Kangas and Pukkala 1996, Carlsson 1999, Andersson et al. 2006, Hurme et al. 2007, Tikkanen et al. 2007, Hauer et al. 2010). The limitation of using PPF is that it only optimizes two objectives in the provision of a two-dimensional efficiency frontier, whereas actual forest management challenges often include multiple conflicting objectives (Calkin et al. 2002).

2.5.5 Multi-objective optimization

In practice, there are multiple objectives to be optimized simultaneously with one objective, possibly influencing one or more other objectives in real-world forest management scenarios (Probert et al. 2011). Multi-objective optimization, belonging to the wide spectrum of operations research models (Kangas and Kangas 2005), is a collection of optimization methods (multi-criteria decision making, Pareto optimization, goal programming, and compromise programming), which can deal with multiple and conflicting objectives for decision-making (Mendoza and Martins 2006).

Multiple objectives such as timber production, biodiversity, carbon stocks or sequestration, ground water recharge, and cultural services are often weighted with different percentages based on their utility for the user (Faith et al. 1996, Seely et al. 2004, Furstenau et al. 2007, Briceno-Elizondo et al. 2008, Schwenk et al. 2012, Cordingley et al. 2016). For instance, Schwenk et al. (2012) implemented a multi-criteria decision method to analyze the trade-offs among three objectives, carbon storage, timber production, and biodiversity. However, the choice of standardized criteria and the hierarchical level of objectives directly influenced the evaluation results (Furstenau et al. 2007). Pareto optimization is an interdisciplinary multi-criteria trade-off analysis that uses a simulation-based optimization approach to arrive at efficient options among multiple objectives (Seppelt et al. 2013). This optimization method generates an efficient Pareto frontier where it is not possible to enhance one objective without another, with a set of potentially feasible ―win-win” combinations. We found very few studies that utilized Pareto optimization to analyze ecological and economic trade-offs (Zhou and Gong 2005, Monkkonen et al. 2014, Garcia-Gonzalo et al. 2015, Trivino et al. 2015). For example, Monkkonen et al. (2014) conducted a trade-off study between economic gains and biodiversity from four tree species and six vertebrate species, using Pareto optimization in a Finnish boreal forest. This group generated Pareto optimal solutions through Pareto frontier, and the results demonstrated that it is possible to achieve —win-win” scenarios with the optimization of both economic and biodiversity objectives. The other two branches of multi-objective optimization include goal programming and compromise programming. The single most important objective is optimized in goal programming, while other objectives are transferred into constraints (D az-Balteiro and Romero 2003). Whereas in compromise programming the multi-objective optimization problem is solved as a single aggregate objective function formed by combining differently weighted objectives (Krcmar et al. 2005).

Nevertheless, there are very few studies that have used multi-objective optimization methods; this technique provides many advantages over other techniques for multi-objective problem-solving in forest management. First, there is no requirement to ascribe monetary value to ecological functions and ecosystem services, which may be inaccurate and imperfect. Second, this technique is a multi-dimensional visualization of trade-offs among multiple objectives, spatially or temporally. Third, it provides a series of satisfactory optimal solutions to planners by presenting all feasible scenarios under specific constraints (Seppelt et al. 2011). Fourth, by tracing out efficient optimal solutions, this technique also assists with mitigating trade-offs through optimization, and facilitates arriving at more efficient forest management decisions.

2.6 Economic and ecological trade-off studies in boreal forests

Although the boreal biome accounts for 30% of global terrestrial phytomass and is one of the world‘s most important bio-geoclimatic areas (Brandt 2009), it remains the least studied biome. We found only 26 studies (19 for Fennoscandia, 7 for Canada) that conducted the economic and ecological trade-off analysis in boreal forests (Table 2.1). Nine studies (six in Fennoscandia, three in Canada) used linear, non-linear, and mixed-integer programming techniques to optimize both spatial habitat suitability and timber revenues for long-term forest management (Hoen and Solberg 1994, Krcmar et al. 2001, Kant 2002, Backeus et al. 2005, 2006, Juutinen and Monkkonen 2007, McCarney et al. 2008, Ohman et al. 2011, Zubizarreta-Gerendiain et al. 2016). Six studies (five in Fennoscandia, one in Canada) used PPF to optimize biodiversity and economic gains, and illustrated that optimum forest management regimes did exist that led to greater timber production with minimum biodiversity losses among several alternatives (Kangas and Pukkala 1996, Carlsson 1999, Andersson et al. 2006, Hurme et al. 2007, Tikkanen et al. 2007, Hauer et al. 2010). Four studies (three in Finland, one in Canada) applied biophysical models based on simulations to analyze the economic and ecological trade-offs involving carbon objectives, cultural services, soil retention, and soil fertility (Pussinen et al. 2002, Garcia-Gonzalo et al. 2007, Raudsepp-Hearne et al. 2010, Pyorala et al. 2014). Pareto optimization has also been used to examine the economic and ecological trade-offs among four objectives (timber production, preservation of biodiversity, reindeer grazing, and recreation) in Sweden (Zhou and Gong 2005), and multiple biodiversity or carbon objectives in Finland (Monkkonen et al. 2014, Trivino et al. 2015). Two studies from Finland and Canada utilized multi-criteria decision making by giving partial weights to economic gains, biodiversity, and carbon sequestration, and the analysis showed that forest management options might be modified by taking advantage of multiple constraints (Seely et al. 2004, Briceno-Elizondo et al. 2008). A multi-objective study in Canada utilized compromise programming to analyze carbon uptake, maintenance of structural diversity, and

Table 2.1. Comparison of economic and ecological trade-off studies in boreal forests.

Methods (Number of studies)	**Countries (Number of studies)**	**Economic objectives**	**Ecological objectives**	**Techniques (Number of trade-off objectives)**
Monetary valuation (1)	Finland (1)	Timber production	Cultural services (tourism)	Monetary valuation (2)
Biophysical models (4)	Finland (3)	Net returns or biomass production	Carbon stocks or sequestration	Biophysical models (2)
	Canada (1)	Maple syrup production	Cultural services, carbon sequestration, soil fertility	Biophysical models (multiple)
Optimization programming (9)	Sweden (3)	Timber revenue or production	Biodiversity, carbon sequestration	Linear programming (2), mixed-integer programming (2)
	Canada (3)	Net returns	Carbon stocks or sequestration, structural diversity	Linear programming (2), non-linear programming (2)
	Finland (2)	Net returns	Carbon balance, biodiversity conservation goal	Linear programming (2)
	Norway (1)	Timber production	Carbon sequestration	Linear programming (2)
Production possibility frontier (PPF) (6)	Finland (3)	Timber production	Habitat suitability or biodiversity	PPF (2)
	Sweden (2)	Timber production	Biodiversity	PPF (2)
	Canada (1)	Timber revenue	Biodiversity	PPF (2)
Multi-objective optimization (6)	Finland (3)	Timber production	Carbon stocks or sequestration, biodiversity	Pareto optimization (multiple/2), multi-criteria decision analysis (3)
	Canada (2)	Net returns	Carbon uptake, structural diversity, biodiversity, carbon storage	Compromise programming (3), multi-criteria decision analysis (3)
	Sweden (1)	Timber production and revenue	Biodiversity, recreation, reindeer grazing	Pareto optimization (4)

economic returns to reveal the most optimal strategy that performed better in the attainment of specific objectives (Krcmar et al. 2005). Monetary valuation techniques have also been employed in the boreal forest to offset the economic losses due to intensive forest management practices by increasing the number of tourists (Ahtikoski et al. 2011).

Several factors may have led to this publication bias in the area of economic and ecological trade-off in the boreal forests in contrast to the tropical and temperate forests. First, negative effects related to the loss of ecological functions and services tend to occur much earlier in tropical and temperate forests, than those in boreal forests. Second, ecological functions and ecosystem services in countries populated by boreal forests remain undervalued, poorly understood, and typically external to the markets because of the abundance of resources (Lee 2004). Finally, economic and ecological trade-off studies are of the least importance for boreal forests, as it is believed that comprehensive environmental regulations and laws are in place to enhance the long-term sustainability of forest ecosystems in boreal residing countries that mitigate economic and ecological conflicts (Chapin et al. 2006).

2.7 The need for trade-off studies in boreal forests

2.7.1 Trade-off analysis under the impact of climate change

Climate change is expected to have the largest influence on boreal forests because of the high rate of global warming in high latitudes over the next century (Diffenbaugh and Field 2013). Changing temperatures, moisture, nutrient availability, and atmospheric CO_2 may alter important ecological functions and ecosystem services, which will impact the boreal biome (Kirilenko and Sedjo 2007). For example, climate change impacts may lead to substantial increases in plant mortality (Allen et al. 2010, Luo and Chen 2015), changes in net biomass (Ma et al. 2012, Chen and Luo 2015) and biodiversity (Chapin et al. 2000, Sala et al. 2000, Foley et al. 2005, Harley 2011, Isbell et al. 2011, Cardinale et al. 2012), increases in natural disturbances such as insects and disease outbreaks (Aukema et al. 2006, Parkins and MacKendrick 2007, Kurz et al. 2008, Boulanger et al. 2013), and increases in the frequency of wildfires (Stocks et al. 1998, Johnstone et al. 2010, Boulanger et al. 2013). Climate change may also have a significant impact on the economic gains from production functions and the provision services of forestry in boreal forest management (Pussinen et al. 2002, Briceno-Elizondo et al. 2008, Hanewinkel et al. 2013). The National Round Table on the Environment and Economy (NRTEE) estimated the economic loss to range between $2 billion and $17 billion per year by the year 2050, due to the impacts of climate change on Canada‘s forest industry (Williamson et al. 2009). Therefore, climate change has implications for both economic gains and ecological losses in boreal forests, necessitating the requirement to study trade-offs across temporal and spatial scales.

Boreal forests in Canada comprise ~ 90% of the total forested area of 417.6 million hectares, and close to one-third of the global boreal forest area (Canadian Council of Forest Ministers 2005). Boreal forest industries contribute significantly to Canada‘s economy, as it is the world‘s leading exporter of forest products (Thompson and Pitt 2003, Wagner et al. 2006), including solid wood products (e.g., timber, lumber, fuelwood, and charcoal), pulp and paper, compositions and engineered wood, chemicals (e.g., acetic acid, acetone, and creosote), bioenergy (e.g., wood pellet), and non-timber products (Grebner et al. 2012). The magnitude of change of Canada‘s climate is anticipated to be substantially higher than that over the previous 100 years, which makes the ecological functions and ecosystem services of boreal forests very vulnerable (Williamson et al. 2009). However, our understanding of the economic and ecological trade-offs of Canada's boreal forests remains limited. Recent synthesis has called for further trade-off studies involving economic and ecological objectives, under the consequences of climate change, to support forest management decisions and policy development for boreal forests (Lempriere et al. 2013). Economic and ecological trade-off analysis will assist with elucidating how mitigation might be integrated with adaptations to climate change under boreal forest conditions (Adamowicz et al. 2003).

2.7.2 Trade-off analysis associated with disturbances

With ongoing climate change, natural disturbances (e.g., fires, drought, severe storms, and damaging insect and disease attacks) are predicted to increase in extent, frequency, duration, and severity in boreal forests (Dale et al. 2001, Boland et al. 2004, Price et al. 2013). Additionally, anthropogenic disturbances linked to human activities, such as timber harvest operations, mining oil and gas, and hydroelectricity production, also have negative impacts on the economic gains and ecological services from boreal forests (Williamson et al. 2009, Venier et al. 2014, Steffen et al. 2015). These disturbances are altering boreal forest ecosystems in fundamental ways, with broad-ranging impacts on soil nutrients, carbon stocks, plant species richness, evenness, composition, age-class distribution, and changes in productivity for timber supply (Thomas et al. 2004, Venier et al. 2014, Clarke et al. 2015). However, the majority of the reviewed trade-off studies in the literature did not consider disturbance impacts, which remains an urgent issue to be addressed to maintain a balance between the economic gains and ecological sustainability of boreal forests, which are susceptible to severe natural and anthropogenic disturbances.

2.7.3 Inclusion of additional ecological functions and ecosystem services

Previous trade-off studies conducted in boreal forests have focused only on the maximization of economic gains, and the maintenance of a certain level of biodiversity (mostly fauna) or habitat provision (Kangas and Pukkala 1996, Carlsson 1999, Seely et al. 2004, Zhou and Gong 2005, Andersson et al. 2006, Hurme et al. 2007, Juutinen and Monkkonen 2007, Tikkanen et al. 2007, Briceno-Elizondo et al. 2008, McCarney et al. 2008, Hauer et al. 2010, Ohman et al. 2011, Monkkonen et al. 2014), structural diversity (Kant 2002, Krcmar et al. 2005), carbon stocks or sequestration (Hoen and Solberg 1994, Krcmar et al. 2001, Pussinen et al. 2002, Seely et al. 2004, Backeus et al. 2005, Krcmar et al. 2005, Backeus et al. 2006, Garcia-Gonzalo et al. 2007, Briceno-Elizondo et al. 2008, McCarney et al. 2008, Pyorala et al. 2014, Trivino et al. 2015, Zubizarreta-Gerendiain et al. 2016), water regulation or supply (Raudsepp-Hearne et al. 2010), erosion protection and soil fertility (Raudsepp-Hearne et al. 2010), and cultural services (Zhou and Gong 2005, Ahtikoski et al. 2011) (Figure 2.2). However, other critical ecological functions and ecosystem services have received less attention in economic and ecological trade-off studies in response to boreal forest management activities. For example, forest-site productivity; linking tree growth with soil and plant nutrients across treatments, is central to the long-term economic and ecological sustainability of boreal forest ecosystems (Anyomi et al. 2014). Intensive forest management strategies that aim to maximize economic gains may not be optimal for the long-term sustainability of boreal forest site productivity. The core concern of site productivity is nutrient depletion, which is associated with biomass removal due to economic activities (MacLellan and Carleton 2003, LeBauer and Treseder 2008). Moreover, intensive forest management, which maximizes economic resources extraction, may also affect plant species diversity. Plant species diversity, including richness, evenness, and composition, reflects the variation, abundance, and ecological relationships among species at both genetic and ecosystem levels (Purvis and Hector 2000). Evidence shows a positive relationship between higher diversity with ecological functions and ecosystem services (Naeem and Wright 2003, Balvanera et al. 2006, Zhang et al. 2012). Plant diversity also serves as a regulatory factor that supports and controls fundamental ecological processes, and directly influences the delivery of some ecosystem services (Hooper et al. 2005, Nelson et al. 2008, Isbell et al. 2011, Mace et al. 2012, Zhang et al. 2012). Economic-ecological trade-off research will benefit from the inclusion of diverse ecological objectives, given the recent series of environmental reviews that have facilitated the understanding of the wide array of biodiversity and ecological functions that boreal forests provide (de Groot et al. 2010, Kurz et al. 2013, Lempriere et al. 2013, Price et al. 2013, Gauthier et al. 2014, Maynard et al. 2014, Venier et al. 2014, Webster et al. 2015) (Table 2.2).

2.7.4 Inclusion of multiple objectives in trade-off analysis with temporal and spatial considerations

The scope of the reviewed literature conducted in boreal forests was generally limited to two objectives. Only three studies considered three objectives (Seely et al. 2004, Krcmar et al. 2005, Briceno-Elizondo et al. 2008), one study focused on four objectives (Zhou and Gong 2005), and very few studies analyzed trade-offs involving multiple objectives simultaneously (Raudsepp-Hearne et al. 2010, Monkkonen et al. 2014) (Table 2.1). Future trade-off analysis shall simultaneously consider additional ecological objectives.

Table 2.2. Primary ecological functions and ecosystem services relevant to the boreal forests.

	Services	Functions	Example of services
Production Functions and Provisioning Services	Provisioning of natural resources, raw materials or energy outputs from boreal forests		
	Raw materials	Species or abiotic components with potential use for building and manufacturing	Lumber, plant fibers, bioenergy, non-timber products such as mushrooms and berries, skins, oils, subsistence values for Indigenous communities and households
	Water supply	Filtering, retention, and storage of fresh water from wetland, surface waters, and groundwater	Provision of fresh water for drinking, irrigation, and transportation
	Food	Provisioning of edible plants and animals for human consumption	Gathering edible plants and hunting animals
	Genetic resources	Presence of species with useful genetic materials	Genes to improve tree resistance to pathogens and pests
	Medicinal resources	Species or abiotic components with potentially use in drugs and pharmaceuticals	Balsam fir, sub-alpine fir, box elder, black maple, moosewood, striped maple, red maple, silver maple, mountain maple, milfoil, boreal yarrow, Siberian yarrow, Alaska wild rhubarb, American sweetflag, white baneberry, cohosh root
	Ornamental resource	Resources for handicraft, worship, decoration, and souvenirs	Feathers or fur used in decorative costumes in Indigenous communities
Habitat Functions and Supporting Services	Ecological structures and functions that are essential to the delivery of other ecosystem services in boreal forests		
	Net primary production	Conversion of solar energy into biomass through photosynthesis	Plant growth
	Nutrient cycling	Acquisition, storage, recycling of nutrients	Nitrogen and phosphorus cycle
	Biodiversity and habitat	Supporting variety and variability of life, and providing breeding, feeding or residing habitat for	Plant diversity, refugium for resident and migratory species, nurseries for spawning

		boreal species	
	Maintenance of genepool	Maintenance of genetic diversity in boreal forest	Endemic species, threatened species (e.g., caribou)
	Hydrological cycle	Movement and storage of water	Evapotranspiration, groundwater retention
Regulation Functions and Regulating Services	Regulation of essential ecological processes and life support systems in boreal forests		
	Climate regulation	Regulation of climate processes	Greenhouse gas production and absorption, Carbon sequestration and storage
	Gas regulation	Regulation of the atmospheric chemicals	CO_2/O_2 balance, stratospheric ozone
	Disturbance regulation	Dampening of environmental fluctuations and disturbances	Fire, insect outbreaks
	Biological control	Control of pest populations and vector-borne diseases through the activities of predators and parasites	Predator control of prey species, natural control of pests and diseases
	Pollination	Movement of floral pollinators	Provision of pollinators (e.g., wind, insect and bird) for plants
	Water regulation	Regulation of hydrological flows in water infiltration, storage, recharge, and discharge in boreal forests	Modulation of the drought-flood cycle
	Waste regulation	Removal or breakdown of organic matter, excess nutrients, and non-nutrient compounds	Water purification, pollution detoxification
	Nutrient regulation	Maintenance of nutrients within acceptable bounds	Regulation of eutrophication in lakes
	Erosion protection, and maintenance of soil fertility	Erosion control of soil, and maintenance of soil fertility in boreal forests	Prevention of soil loss by wind and runoff
	Soil formation and regeneration	Natural processes in soil formation and regeneration	Weathering of rock, accumulation of organic material
	Air quality regulation	Capacity of ecosystems to extract aerosols and chemicals from the atmosphere	Capturing dust particles
Information Functions and Cultural Services	Enhancing emotional, psychological, and cognitive benefits for human well-beings		
	Recreation and tourism	Opportunities for recreation and tourism	Recreation-related activities in boreal forests
	Cultural inspiration and heritage	Landscape features or species with inspirational value to	Inspirational value, books, paintings in Indigenous communities

		human arts and heritage	
	Aesthetic appreciation	Aesthetic quality of the boreal forests	Natural scenery, structural diversity
	Spiritual and religious inspiration	Landscape features or species with spiritual and religious significance	Religious meaning in Indigenous communities for a sense of belonging
	Education and science opportunities	Opportunities for education, training, and research	Educational and scientific value

Source: adapted from de Groot et al. (2010).

Despite recent progress, the combination of spatially explicit and temporally dynamic simulations with optimization approaches, for truly multi-objective purposes, has thus far remained poorly developed. We propose the use of multi-objective optimization as a preferred method to provide a series of satisfactory optimal solutions for forest management, and to bridge the gap for economic and ecological trade-off analysis with multiple ecological objectives across both spatial and temporal scales, by integrating modeling techniques. Spatial concerns may be added by using adjacency constraints or spatially explicit landscape simulation models in multi-objective optimization, while the temporal scale may be included by conducting simulation scenarios that span the entire planning horizon. Feedback from multiple options of forest management decisions can be created as multiple scenarios using simulation models. The parameters derived from these scenarios may then be employed, for decision-making and future realistic predictions, using the multi-objective optimization technique.

Moreover, the extent and magnitude of climate change impacts on the ecological functions and services of the boreal forests remain uncertain, as do the economic consequences (Gauthier et al. 2015). However, an assessment of economic and ecological trade-offs for forest management decision-making under the effects of climate change will necessitate the consideration of the uncertainties that are associated with projected climate change scenarios (Hanewinkel et al. 2013). These uncertain scenarios may have to rely on simulation models, and trade-off analysis might be conducted by assessing sensitivities of economic opportunities and ecological functions and services to the projected climate change using multi-objectives techniques (Trivino et al. 2015)

2.7.5 Inclusion of social aspects

It is also important to develop forest management policies through exploring multi-objectives modeling techniques that balance the needs of economic, ecological, as well as social sustainability (Chapin et al. 2003). Especially in the context of boreal forests, where nearly 80% of the Indigenous communities reside in the productive forest areas, and Indigenous Peoples rely on boreal forest resources for nutritional, social, cultural, spiritual, and other services and well-beings (Stevenson and Webb 2003). It is also widely recognized that the success of crown forest management mainly depends on the active participation of Indigenous communities (Saint-Arnaud et al. 2009). Therefore, Indigenous Peoples and their social-economic aspects need to be considered in the future economic and ecological trade-off studies in their traditional territories in boreal forests.

2.8 Conclusions

Although intensive forest management practices maximize economic gains, the long-term impacts of these management practices on ecological functions and services have not been fully investigated. This review paper has examined the economic and ecological trade-off methods that are commonly employed in making forest management decisions, including monetary valuation, biophysical models, optimization programming, production possibility frontier, and multi-objective optimization. This review revealed that: (i) economic and ecological trade-offs are poorly understood for boreal forests; (ii) the analysis of economic and ecological trade-offs often includes limited ecological functions and ecosystem services; and (iii) multiple economic and ecological objectives are rarely considered in the trade-off studies of boreal forests.

Therefore, it remains uncertain how economic activities might best maintain and support multiple ecological functions and services in boreal forests under ongoing global climate change and increasing anthropogenic disturbances. We propose the use of multi-objective optimization techniques toward the realization of sustainable and optimal forest management solutions to support management decisions and policy development in the boreal forest and beyond.

CHAPTER 3: ECONOMIC ANALYSIS OF FOREST MANAGEMENT ALTERNATIVES: COMPOSITIONAL OBJECTIVES, ROTATION AGES, AND HARVEST METHODS IN BOREAL FORESTS

3.1 Abstract

Timber production and economic gain are important forestry objectives. Boreal forests have long been an important contributor to commodity products. However, in recent decades, commercial production in the boreal forest industry is undergoing a fundamental shift from traditional wood products to multiple value-added products including residues for bioenergy production. In order to help decision makers select economically optimal forest management alternatives, we conducted an empirical study, the first of its kind, to explore the impact of varying silvicultural intensities, forest compositions, rotation ages, and harvest methods on profits in a portion of the boreal forest in Northwestern Ontario. We found that silvicultural intensity, forest composition, rotation age, and harvest method significantly affected profit. The profit was on average the highest from coniferous stands, followed by mixedwood and broadleaved compositions. The profits in mixedwood stands increased continuously with rotation age using both Full-Tree to Roadside Tree-Length-to-Mill harvesting method (FT-TL) and Full-Tree to Roadside Shortwood-to-Mill method (FT-SW), and increased with rotation age but decreased at late-succession stage using Cut-to-Length method (CTL). The profits were on average higher using FT-TL than using FT-SW and CTL. The maximum profit ($3305 /ha) was solved for low silvicultural intensity (conifer – conifer), with a rotation

age of 100 years, using the FT-TL harvest method. This analysis provides an example of finding economically optimal forest management solutions.

3.2 Introduction

As one of the world‘s most important bio-geoclimatic areas (Bradshaw et al. 2009, Brandt 2009), boreal forests account for 30% of global terrestrial phytomass and constitute approximately 45% of the global growing stock of timber, which is an important source of economic gain (Vanhanen et al. 2012). Boreal forests in Canada comprise about one-third of the global boreal forest area (Canadian Council of Forest Ministers 2005), and contribute significantly to the Canadian economy (Thompson and Pitt 2003, Wagner et al. 2006). Although boreal forests have been primarily used for production of commodity products such as lumber, pulp and paper products, in recent decades, commercial production in boreal forest industry is undergoing a fundamental shift from traditional wood products to multiple value-added forest products, including increasing economic potential of forest residues for bioenergy production (Mabee et al. 2011, Puddister et al. 2011, Thiffault et al. 2011). This shift is in line with the changing demand trends of global markets in natural resource consumption (Foley et al. 2005).

In order to produce a range of value-added products from forest fibre, a number of forest management alternatives with different economic gains have been applied to the boreal forests (Pyorala et al. 2014). Previous economic analyses have mainly focused on the impacts of individual silvicultural treatments (Bell et al. 1997, Tong et al. 2005, Cao et al. 2008, Mathey et al. 2009, Lindenmayer et al. 2012, Pyorala et al. 2014, Halbritter and Deegen 2015, Tahvonen 2016). Review of financially viable, intensive forest management alternatives for broadleaved stands (Anderson and Luckert 2007), stand-level of a profit maximization with the optimal rotation age and harvest volume (Yin and Newman 1997, Yin and Sedjo 2001), stand-level economic analysis comparing the net present values of various silviculture activities and harvesting prescriptions of boreal mixedwoods (Rodrigues 1998), and financial analysis of several alternative management scenarios of boreal mixedwoods (Yemshanov et al. 2015) have also been reported. However, the combined effects of silvicultural intensity, forest composition, rotation age and harvesting method associated with forest management alternatives remain unexplored.

Forest management alternatives include a range of silvicultural operations and intensities to achieve specific objectives (e.g., stand structure, density, composition, rotation age, and control of site productivity) that can provide a framework for decision making on economic gains from forestry operations (Bell et al. 2008, Duncker et al. 2012a). Forest management alternatives in the boreal forest include two dominant regeneration methods (natural and artificial) to control changes in species composition from the current stand condition to the desired stand condition. Site preparation, planting or seeding, tending, and thinning are silvicultural operations manipulated to different intensities in renewing the forest and achieving different forest compositions (Fu et al. 2007, Bell et al. 2008). Where pre-disturbance composition contains a broadleaved species, no silviculture, low and high silvicultural intensities usually lead to broadleaved, mixedwood, and coniferous stands, respectively (Soalleiro et al. 2000, Montigny and MacLean 2006).

Silvicultural intensity associated with controlling species composition can affect fibre production and tree growth in boreal forests (Montigny and MacLean 2006, Bell et al. 2008). Coniferous and broadleaved species usually generate wood products with different qualities and values, therefore the economic returns differ strongly among forest stands with different tree species compositions. Coniferous species are usually harvested for saw logs, while the majority of broadleaved tree species are harvested for pulp logs and bioenergy with relatively lower economic values (Mathey et al. 2009). As for gross total volume, mixed-species stands may be more productive than the average of single-species counterparts at late stages of forest succession in both managed and natural forests (Knoke et al. 2008, Zhang et al. 2012). In addition, mixed plantations are less vulnerable to disturbances such as insect outbreaks or disease (Jactel and Brockerhoff 2007), and may have a lower financial risk (Yachi and Loreau 1999). However, when considering costs, monocultures could be more efficient and cheaper to manipulate and produce homogenous products (Paquette and Messier 2009), while mixed-species stands have higher harvesting costs per unit volume due to demand for higher harvester skill levels and logistical difficulties in operations (Royer-Tardif and Bradley 2011).

The choice of forest rotation age (i.e., one complete growing cycle of economic products) also directly impacts the product mix through size and distribution of trees in the stand (Liski et al. 2001, Asante and Armstrong 2012). While searching for the optimal rotation age with maximum biomass production is the key to developing an economically productive forest, short rotations motivated by short-term profits may result in degraded forest stands that do not contribute to the long-term ecological health and social benefits (Erickson et al. 1999). Although longer ecological rotations may not be economically optimal in terms of mean annual timber production (Pyorala et al. 2014), they may one day yield additional value from higher quality wood products, while also contributing to maintaining objectives related to biodiversity and ecosystem functioning, including maintenance of gap dynamics stage, accumulation of soil organic matter, and provision of biodiversity and social benefits (Curtis 1997, Erickson et al. 1999, Harmon and Marks 2002, Thompson et al. 2009).

However, tree mortality increases with forest aging (Luo and Chen 2011), accompanied with reduced net biomass production (Pretzsch et al. 2014, Chen et al. 2016a). Long rotation ages could also result in decayed wood with low merchantable volume and economic value (Willcocks 1997).

While wildfire is the major stand-replacing natural disturbance in the boreal forest (Landres et al. 1999, Ward et al. 2014), anthropogenic disturbances, primarily harvesting, also play an important role in shaping forest structure and composition, both of which affect merchantable volume. In Canadian boreal forests, full-tree harvesting (i.e., removing the entire above-stump portion of the tree including tops and branches from site to maximize biomass extraction from the forests) and stem-only harvesting (cut-to-length or tree-length for saw logs and pulp logs, leaving logging residues including tops and branches on site) are common operations (Canadian Council of Forest Ministers 2005). Increased demand for forest residues in bioenergy is better suited to a full-tree harvesting system with a lower harvesting cost (Mabee et al. 2011, Puddister et al. 2011, Thiffault et al. 2011). Although stem-only harvesting provides a slightly better benefit in terms of lumber recovery per cubic metre, net revenue from the full-tree harvesting is higher (Plamondon and Pagé 1997, Adebayo et al. 2007).

Despite the diverse forest management alternatives associated with varying silvicultural intensities, compositional objectives, rotation ages, and harvest methods used in boreal forests (Soalleiro et al. 2000, Montigny and MacLean 2006, Saunders and Arseneault 2013), there exists no comprehensive economic analysis exploring economic efficiency and profitability associated with forest management alternatives. In order to provide decision-makers with empirical evidence that might help select optimal forest management alternative, we analyzed how different forest management alternatives affect the profits ($/ha). The specific objectives are: (i) to determine the impact of silvicultural intensity on compositional objectives, (ii) to assess gross total volume (GTV; m^3/ha) and net merchantable volume (NMV; m^3/ha) from stands of different species compositions, rotation ages and harvesting methods, and (iii) to estimate the costs and profits associated with different combinations of forest management alternatives.

3.3 Materials and methods

3.3.1 Study area and data collection

Our study area is located north of Lake Superior and west of Lake Nipigon, approximately 100 km north of Thunder Bay, Ontario, Canada, between 49°44'N and 49°65'N, and 89°16'W and 90°13'W. This area is characterized by warm summers and cold, snowy winters. A mean annual temperature of 1.9°C and mean annual precipitation of 824.8 mm were recorded at the closest meteorological station in Cameron Falls, Ontario, Canada (Environment Canada 2016). Dominant tree species include trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh), jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill) B.S.P.), white spruce (*Picea glauca* (Moench) Voss), and balsam fir (*Abies balsamea* (L.) Mill.). Broadleaved and coniferous stands were defined as having > 65% broadleaved or coniferous tree species composition by basal area, while all other stands were classified as mixedwood stands (Hume et al. 2016b). Stand replacing wildfire is the dominant natural disturbance in the study area, with an average fire return interval of approximately 100 years, resulting in a mosaic of stand ages in the area (Senici et al. 2010). There has been a

40-year history of commercial logging with diverse harvest methods in the study area (Shrestha and Chen 2010).

We randomly selected chronosequences of stands in four age classes: 34, 99, 147, and 210 years since fire with the use of forest resource inventory maps (Table 3.1), representing late stem exclusion, early canopy transition, late canopy transition, and gap dynamic stages of stand development, respectively (Chen and Popadiouk 2002). Within each of the selected stands, we established a randomly located 0.04-ha (11.28-m radius) fixed-area circular plot, located > 50 m from the forest edge, to represent the stand (Luo and Chen 2015). The stands were allocated several kilometers apart from each other to ensure that the sampled stands were interspersed and spatial autocorrelation and edge effects were minimized (Legendre and Legendre 1998, Harper et al. 2005). We recorded the species, diameter at breast height (DBH, 1.3 m above root collar), and total heights of all trees within each plot. The basal area by species was summed at the plot level and then scaled up to per ha.

3.3.2 Forest management alternatives

In order to explore the impacts of silvicultural intensity on species composition, rotation age, and harvesting method on economic profitability, we examined three initial stand conditions (defined as species compositional types: broadleaf, mixedwood, and conifer), silvicultural intensities (no, low, high) leading to three compositional objectives (broadleaf, mixedwood, and conifer), eight rotation ages (50, 75, 80, 85, 90, 95, 100, 125 years), and three harvest methods (Full-Tree to Roadside Tree-Length-to-Mill, Full-Tree to Roadside Shortwood-to-Mill, Cut-to-Length), resulting in 648 forest management alternatives (i.e., 3 initial stand

Table 3.1. Characteristics of the 36 sample stands in the boreal forests of Ontario, Canada.

				Stand composition (%)^c					
Age	Overstorey^a	N	Basal area (m^2 ha^{-1})^b	Trembling aspen	White birch	Jack pine	Spruce spp.	Balsam fir	Others
34	B	3	26 (1)	93 (3)	4 (4)	1 (1)	1 (1)		1 (1)
	C	3	28 (2)	4 (2)		95 (3)	1 (1)		
	M	3	13 (1)	52 (4)		41 (6)	7(5)		
99	B	3	51 (7)	91 (2)	3 (2)		2 (2)	1 (1)	4 (1)
	C	3	52 (2)	3 (2)		43 (12)	50 (17)	4 (3)	
	M	3	43 (5)	40 (12)	16 (11)	10 (6)	15 (8)	18 (3)	2 (1)
147	B	3	58 (8)	85 (3)	7 (4)		5 (1)	2 (1)	1 (1)
	C	3	51 (9)	1 (1)	2 (2)	53 (27)	37 (26)	7 (1)	
	M	3	35 (1)	45 (6)	21 (8)		10 (3)	23 (4)	2 (2)
210	B	3	41 (3)	54 (22)	24 (18)		10 (6)	10 (4)	2 (1)
	C	3	40 (8)	5 (5)	7 (4)		36 (18)	50 (17)	2 (1)
	M	3	46 (3)	11 (4)	39 (5)	5 (3)	38 (7)	7 (3)	

Notes: Each age-overstorey combination has three replications.

[a] Overstorey types: B = broadleaf, C = conifer, M = mixedwoods.

[b] Values are means with 1 stand error in parentheses.

[c] The ‗Others‘ category includes *Salix* spp. and *Prunus pensylvanica,* which were not considered as economic values in our study.

condition × 3 compositional objectives × 8 rotation ages × 3 harvest methods × 3 replicates) (Figure 3.1). Our analysis was based on the needs of existing sawmills and a pulp mill belonging to Resolute Forest Products Inc., located in three Northern Ontario communities (Thunder Bay, Atikokan, and Ignace). Resolute leases a large area of boreal forest from the Crown to collect biomass feedstocks for its mills.

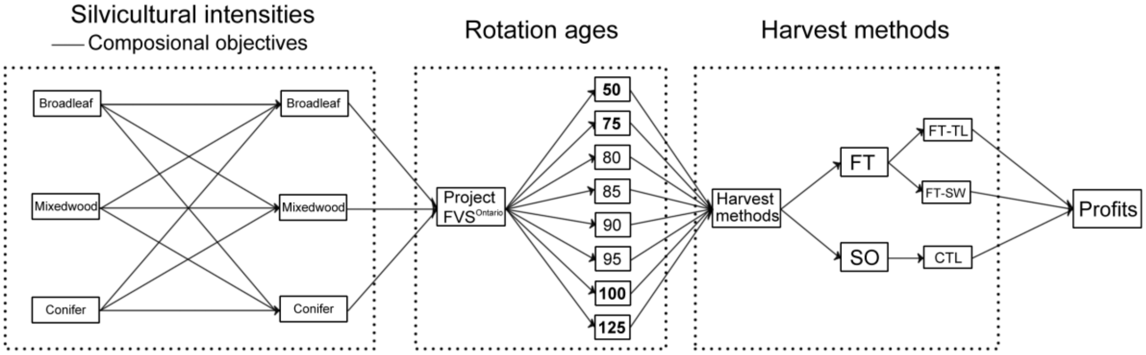

Figure 3.1. Conceptual diagram of forest management alternatives showing the package of silvicultural intensities leading to different compositional objectives, rotation ages, and harvesting methods. FT represents full-tree harvesting, including Full-Tree to Roadside Tree-Length-to-Mill (FT-TL) and Full-Tree to Roadside Shortwood-to-Mill (FT-SW). SO represents stem-only harvesting, includes cut-to-length (CTL). FVS$^{\text{Onario}}$ is Forest Vegetation Simulator that projects gross total volumes of each forest management alternative based on current size and calibrated values of empirical stand conditions.

3.3.3 Silvicultural treatments

Species composition is controlled by silvicultural intensity. Based on Ontario‘s Silvicultural Guide (OMNR 2003), natural regeneration (no silvicultural treatment) after harvesting or natural disturbances (e.g., fire, insect, disease, or severe weather events) that leads to the development of broadleaved species is only applicable to stands whose pre-disturbance composition contains a broadleaved species through self-replacement succession, such as trembling aspen and white birch (Chen et al. 2009, Ilisson and Chen 2009, Landhausser et al.

2010). If coniferous seedlings are planted after mechanical site preparation, followed by low silvicultural investments such as minimal chemical tending with glyphosate, triclopyr or 2,4-D and partial cutting to suppress broadleaved species, results are mixedwood (Man et al. 2011, Royer-Tardif and Bradley 2011, Venier et al. 2014). With conifer dominance as a forest compositional objective, coniferous species are planted or seeded and the resulting plantations treated with intensive silviculture including mechanical or chemical treatments that effectively eliminate the growth of broadleaved species (Fu et al. 2007, Wang and Chen 2010).

The silvicultural costs ($/ha), including the costs of mechanical site preparation, chemical site preparation, aerial seedling, planting, chemical tending, slash pilling, slash burning, direct costs, overhead and administration associated with forest management alternatives, were estimated based on 2016 average prices in Thunder Bay (Ministry of Natural Resources 2011, Ministry of Natural Resources and Forestry 2015). Only overhead and administration costs of harvesting were considered in forest management alternatives with no silvicultural investments. Alternative silvicultural techniques including different levels of site preparation, planting or seeding, and chemical tending were used to achieve the same objectives of mixedwood and conifer forests (OMNR 2003). Planting depended on initial site condition, original species composition, and desired species composition for the new stands, and was the dominant silvicultural investment to regenerate to conifer-dominated mixedwood and pure coniferous stands in the study area (MacDonald 2000).

3.3.4 Growth projection and rotation ages

We used Forest Vegetation Simulator (FVS$^{\text{Ontario}}$) — a non-spatial, individual-tree growth model specifically for Ontario — to project expected GTV of each forest management alternative based on current size and calibrated values of empirical stand conditions (Woods and Robinson 2007). The model simulates changes in diameter increment of individual trees using calibrated values of the tree measurements (species, tree height, DBH, and number of trees per ha, site index), assuming equal spacing between existing trees and no intermediate silvicultural operations. We selected four major projected rotation ages: 50-year as the ecologically and biologically acceptable rotation, 75-year as the operational rotation age under tenure, 100-year as recommended by law in Ontario, and 125-year as the maximum volume accumulation with optimal ecological benefits in boreal forests (Willcocks 1997, Bell et al. 2011). We also extended more rotation ages that varied by five year intervals between 75- to 100-year, rotation ages of 80, 85, 90, 95 years. Existing inventory conditions of 34-year old stands were used to project volumes to rotation ages of 50, 75, 80, 85, 90, 95 years, while empirical data from 99-year stands were used to project to rotation ages of 100 and 125 years.

3.3.5 Harvesting methods and net merchantable volume

The harvesting operations within the forest and the transfer of materials to mills were carried out by independent contractors hired by Resolute. The contractors were in charge of felling, bucking, sorting, loading, and transportation. We considered both full-tree (FT) and stem-only (SO) harvesting in our study, each involving a number of activities and different types of machinery working together. An FT system includes Full-Tree to Roadside Tree-Length-to-

Mill (FT-TL), Full-Tree to Roadside Shortwood-to-Mill (FT-SW), and Full-Tree to Roadside Chip-to-Mill (FT-CH), while stem-only harvesting system includes Cut-to-Length (CTL). The FT harvesting system comprises a feller buncher, a skidder, a processor or a stroke delimber and slasher. Trees with branches and tops intact are felled at an acceptable stump height according to the Scaling Manual (Ontario Ministry of Natural Resources 2007), and dragged to the cutblock roadside. Then logs are delimbed and processed at the roadside as tree-length to mill (FT-TL) or shortwood (FT-SW) with specific targets (e.g., 10") to mill with transportation by truck. In FT-CH, whole trees are brought by a grapple skidder to the roadside, where they are processed using delimber-debarker-chipper system into pulp chips. FT-CH is the most commonly used harvest method for broadleaved species in boreal forests. CTL comprises a single grip harvester and a shortwood forwarder, in which trees are felled, delimbed, cross-cut with target log lengths, topped to a minimum size (3.5"), and sorted in at the stump site according to log quality specifications (Ontario Ministry of Natural Resources 2007). A forwarder then takes the sorted logs to the roadside, where they are transported to mill.

We considered three major harvest methods: FT-TL, FT-SW, and CTL, aiming for coniferous lumber, as well as a fourth: FT-CH, especially for broadleaved or coniferous chips and bioenergy used in collaborating mills. For coniferous species with DBH ≥ 10 cm, we considered FT or CTL aiming for saw logs. For broadleaved species, trembling aspen trees were chipped with FT-CH into pulp logs, while white birch and any logs produced with a minimum diameter below 5 cm were only harvested with FT-CH for biomass in according to information provided to us by Resolute.

We calculated the gross total volume (GTV) for each tree using Honer‘s equations as below: (Honer 1983):

$$GTV_t = \frac{0.0043891 \times D^2 (1 - 0.04365 \times b_2)^2}{(c_1 + 0.3048 \times c_2 / H)} \qquad (1)$$

where: GTV_t = gross total volume (m^3), D = diameter at breast height (1.3 m) outside bark (cm), H = total tree height (m), b_2, c_1 and c_2 = species specific regression coefficients (b_2 = 0.127 , c_1 = -0.312, c_2 = 436.683 for trembling aspen; b_2 = 0.176 , c_1 = 2.222, c_2 = 300.373 for white birch; b_2 = 0.151 , c_1 = 0.897, c_2 = 348.530 for jack pine; b_2 = 0.164 , c_1 = 1.588, c_2 = 333.364 for black spruce; b_2 = 0.176, c_1 = 1.440, c_2 = 342.175 for white spruce; b_2 = 0.152 , c_1 = 2.139, c_2 = 301.634 for balsam fir). Individual tree GTVs were summed and scaled to a per ha level. GTV was then converted into net merchantable volume (NMV) based on the wood fibre recovery factor of the four harvesting methods from fibre utilization research in Northern Ontario (i.e., FT-TL: 82.1%, FT-SW: 77%, FT-CH: 88.7%, and CTL: 87.4%) and the Scaling Manual for clearcut operations. The most efficient systems in terms of fibre recovery are FT-CH and CTL, which provide a better yield in terms of recovery of merchantable wood. Residues from tops, barks, and branches in FT systems are also collected and processed by a mobile grinder into hog fuel (green metric ton, GMT/ha^{-1}) (Pare et al. 2011). Biomass residuals for bioenergy from FT harvesting were calculated based on allometric equations (Lambert et al. 2005). The FT system is the major logging system that is feeding both sawmill and pulp mill in mixedwood conditions and is used for extracting renewable bioenergy from forest residues for extra economic gains.

3.3.6 Economic analysis

The profit of each forest management alternative was calculated by subtracting the present costs from present benefits, and further analysis was conducted to search for optimal forest management combination scenarios that resulted in a maximum economic gain. The mathematical expression of calculating profits is shown in equation 2, which can be viewed as an expression of a profit maximization problem defined on simultaneous management scenarios.

$$\sum_{aijk=1}^{n} P_{aijk} = \sum_{aij=1}^{n} R_{aij} - \sum_{aijk=1}^{n} C_{aijk} \qquad (2)$$

where: P = profits, R = revenues, C = costs, a = rotation ages (i.e., 50, 75, 80, 85, 90, 95, 100, 125 years), i = harvest methods (i.e., FT-TL, FT-SW, CTL), j = product types (i.e., lumber, softwood market pulp, newsprint, hog fuel, pellet, and hardwood market pulp), k = cost types (i.e., harvest costs, transportation costs, production costs, and silvicultural costs), which are all in 2016.

The economic values of lumber, chips, hog fuel, and pellets constitute the total product value of the stand according to FT and CTL harvest systems (Figures 3.2 and 3.3). Based on all trees from each empirical or simulated stand composition, rotation age, and harvest method, the total value summation was determined for all products per hectare for each forest management alternative. Local sawmills produce lumber with 90% stud or better, as well as some by-products such as: softwood chips (with species distribution of 49% spruce for newsprint and 51% other coniferous species for market pulp); hog fuel and pellets for co-generation to produce electricity and heat for the mills and Atikokan (Power) Generating Station in northwestern Ontario. The mills use their manufacturing waste (i.e., chips and barks), harvesting residue (i.e., branches and tops), and whole trees with diameters ≤ 5 cm as hog fuel to generate electricity, which is either used internally or sold back to the Ontario grid. The low-pressure steam extracted from turbines is used for drying and heating needs of the mills.

We estimated efficient utilization of inputs for lumber, softwood pulp, newsprint, hog fuel and pellets, respectively, based on the proportion of NMV and conversion factors either from Forest Engineering Research Institute of Canada (FERIC) (Plamondon and Pagé 1997, Shahi et al. 2011) or Resolute empirical data from FT and CTL systems (Table 3.2). Current mean market prices of final products were estimated based on present prices (2016) to calculate the economic gains of each final product produced from each forest management alternative on per hectare basis. For example, lumber price was calculated by averaging prices for SPF (spruce–pine–fir) 2×4, with grading levels of stud grade, #1 and #2, and economy from Random Length price statistics (Random Lengths 2016); the prices for softwood market pulp, hardwood market pulp, and newsprint were obtained from RISI current average prices (RISI 2016); and the prices of hog fuel and pellets from FutureMetrics (FutureMetrics 2016). The total economic gains per hectare for each forest management alternative were calculated based on the final product values of lumber, softwood market pulp, hardwood market pulp, newsprint, hog fuel and pellets from each stand.

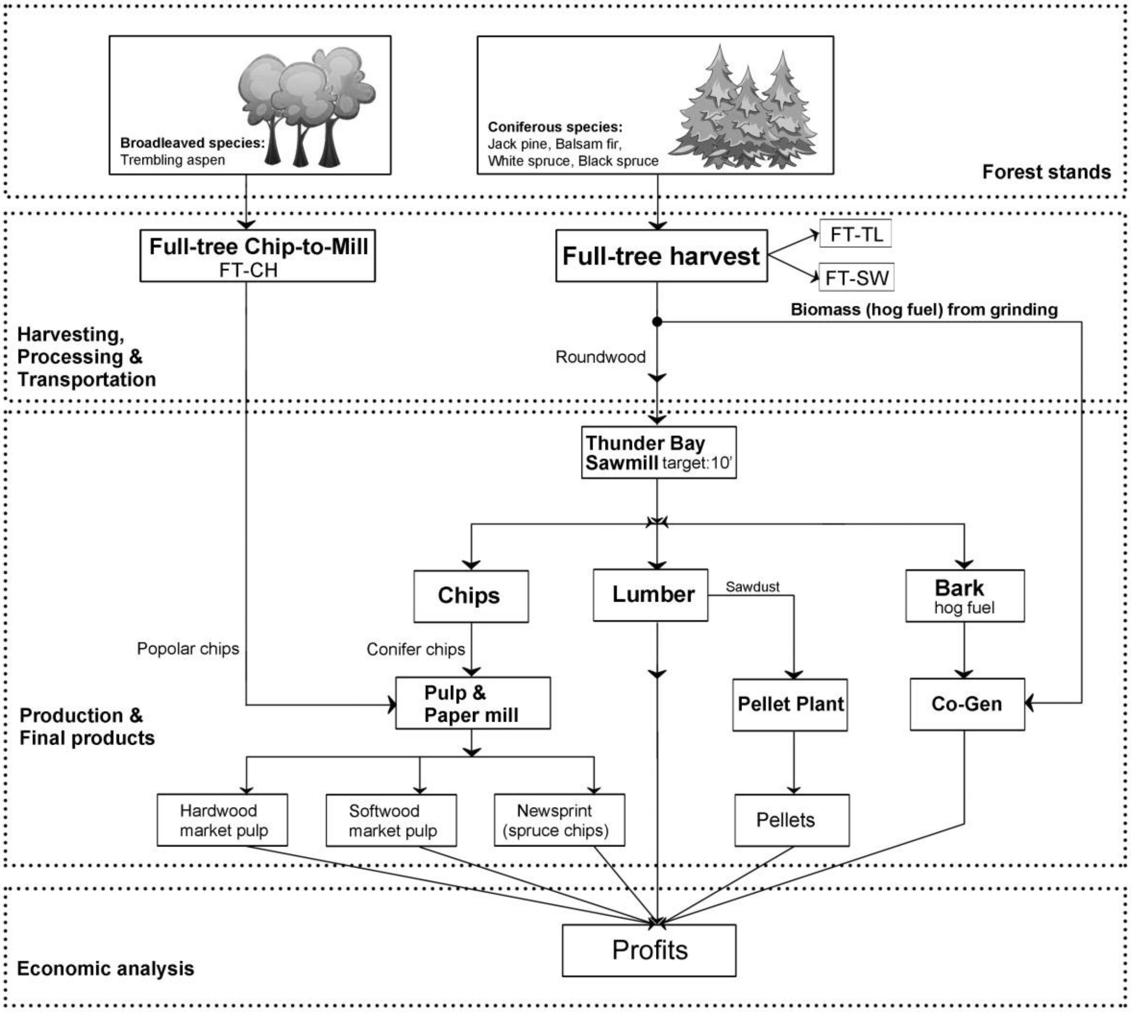

Figure 3.2. Flow chart of full-tree harvest method including Full-Tree to Roadside Tree-Length-to-Mill (FT-TL), Full-Tree to Roadside Shortwood-to-Mill (FT-SW), Full-Tree to Roadside Chip-to-Mill (FT-CH). Co-gen means co-generation of electricity and steam.

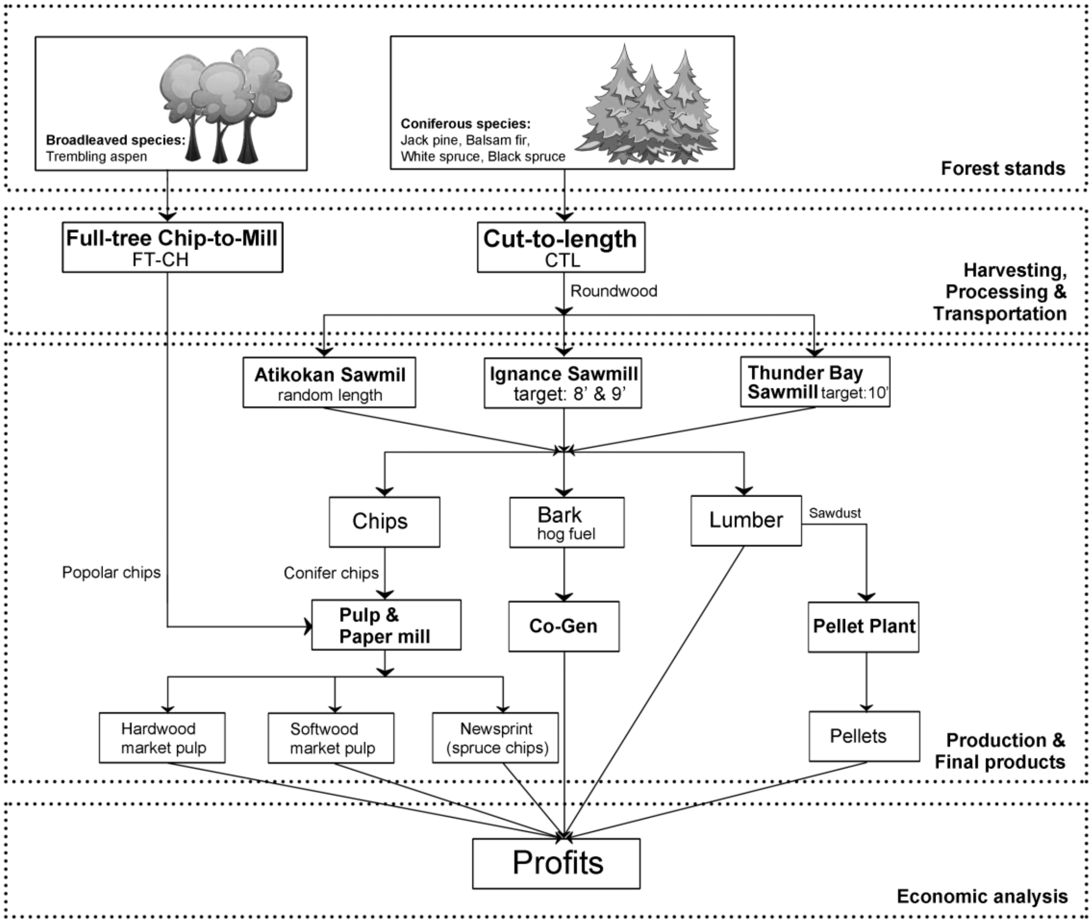

Figure 3.3. Flow chart of cut-to-length (CTL) harvest method. Co-gen means co-generation of electricity and steam.

We used the year 2016 prices of lumber, softwood pulp, newsprint, hog fuel, pellets, and hardwood market pulp, and the year 2016 costs of silviculture, harvesting, processing, transportation, and ―all-in" delivered costs (i.e., production, shipping, distribution, and administrative expenses). We, therefore, did not use discount rates in our calculations. In order to estimate the profit of each forest management alternative, we also calculated the costs of production for each product. These included mill gate costs obtained from costs of harvesting, processing, and transportation for each harvest method (i.e., \$60 /m^3 for CTL,

\$58.5 /m^3 for FT-SW, \$55 /m^3 for FT-TL, \$45 /m^3 for FT-CP, and \$35 /GMT for grinding the biomass based on the current local market data in Thunder Bay in 2016). ―All-in" delivered costs, production costs, shipping costs, distribution costs, and administrative expenses for multiple products were obtained from Resolute (Table 3.2). The profit of each forest management alternative was calculated by subtracting the present costs from the total present benefits, and further analysis was conducted to search for optimal forest management combination scenarios that resulted in a maximum economic gain.

3.3.7 Dynamic scenario analysis

We used dynamic scenario analysis to examine how profit was affected by silvicultural intensity, species composition, rotation age, and harvesting method directly, and by forest composition through silvicultural intensity indirectly (Shipley 2000) (Figure 3.4). To evaluate the hypothesized causal relationships among factors using dynamic scenario analysis, we converted the categorical independent factors into numerical factors: silvicultural costs represented silvicultural intensities, proportions of conifers represented forest compositions, and fibre recovery factors represented harvest methods. We fitted two path models using direct and indirect effects. The direct effects model included: silvicultural intensity on profit, forest compositions on profit, rotation ages on profit, harvest methods on profit (equation 3), and the indirect effects model with silvicultural intensity on profit through forest compositions (equation 4). We modeled the profit in a multiple regression framework, the bivariate relationship were also explored.

Table 3.2. Estimated conversion factors for one unit inputting wood to diverse final products from full-tree methods (FT) and cut-to-length (CTL) harvest systems in the mills, and market price and —all-in” delivered costs used for the final products.

	Conversion factors			**Price**	**Cost**
Product	FT (%)	CTL (%)	Volume in m^3 needed to produce one unit product	Market price	—All-In” delivered cost [f]
Lumber	47.3%	48.9%	2.36	480 $/MFBM [b]	280$/MFBM [b]
Softwood market pulp	20%	20%	5.4	1100$/ODMT [c]	700$/ODMT [c]
Newsprint	19.3%	19.3%	2.6	700$/ODMT [c]	620$/ODMT [c]
Hog fuel	3%	3%	5	140$/MWh [d]	90$/MWh
Pellet	10.4%	8.8%	2.05	186.2$/ODMT	105$/ODMT [c]
Total	100%	100%			
Hardwood market pulp	100% [a]	0	4.6	900$/ODMT [c]	700$/ODMT [c]

[a] Pulp mill directly accepts poplar chips (i.e., chips of trembling aspen) for hardwood market pulp only using FT method.

[b] MFBM means thousand board-feet.

[c] ODMT means oven dried metric ton.

[d] GMT means green metric ton with 50% moisture content.

[e] MWh means megawatt-hours.

[f] —All-in” delivered cost is the total cost combining of production costs, shipping cost, distribution costs, and administrative expense for the multiple final products are also estimated based on the local market data in 2016.

$$P \sim p_1 S + p_2 C + p_3 R + p_4 H + \varepsilon \qquad (3)$$

$$C \sim p_5 S + \varepsilon \qquad (4)$$

where P = profits, S =silvicultural intensity, C= compositions, R = rotation ages, H = harvest methods, p = standardized path coefficients, Ɛ = independent error term for corresponding regression.

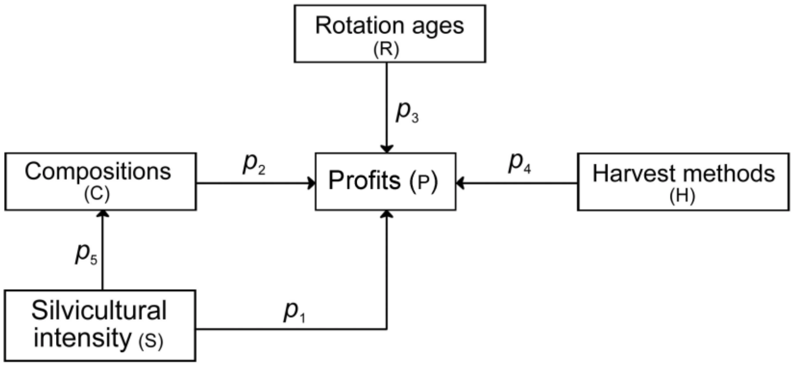

Figure 3.4. Schematic diagram of hypothesized causal relationships among profits, silvicultural intensity, compositions, rotation ages, and harvest methods. The direction of direct effects, as indicated with *arrows* and marked with path coefficients ($p_{1\text{-}5}$), may be positive, negative or neutral.

The assumptions of homogeneity and normality were violated based on Shapiro-Wilk‘s and Barlett‘s tests, respectively. Thus, we bootstrapped the estimates of regression coefficients by using the ‗*boot*‘ package in R (Canty and Ripley 2016) with 4,999 iterations to generate 95% confidence intervals (CIs) (Adams et al. 1997). When the 95% CIs did not cover zero, regression coefficients were considered significantly different from zero. We compared linear and quadratic functions for each variable and selected the best bivariate relationships for rotation age on profit, we used a linear relationship for silvicultural intensity, forest composition, and harvest method on profit, based on Akaike Information Criterion (AIC): the simpler model was selected when the difference in AICs between alternative models was <2 (Burnham and Anderson 2002). All statistical analyses were conducted in R version 3.3.2 (R Development Core Team 2016).

3.4 Results and Discussion

3.4.1 Relationships between silvicultural intensity and compositions

The effect of silvicultural intensity on forest composition demonstrated that no silviculture, low and high silvicultural intensities generally led to broadleaf, mixedwood, and conifer dominant stands, respectively (Table 3.3). However, we found two exceptions, when the original stand was dominated by broadleaved species, high silvicultural intensity (chemical tending for all the sites twice) led to mixedwood stands, and when the original stand was dominated by coniferous species, low silvicultural intensity (chemical tending for 40% of the sites once) led to conifer dominant stands (Table 3.3). The results of dynamic scenario analysis also showed that silvicultural intensity had a significant positive (+0.71, $P < 0.001$) impact on forest composition (Figure 3.5). The coefficients obtained from dynamic scenario analysis were standardized prediction coefficients, showing that every 1 unit increase in silvicultural intensity ($1 silvicultural cost) yielded an increase of 0.71 percent dominance by coniferous species. The results were consistent with previous findings that silviculture intensity influences stand composition, and higher intensity usually yielded higher conifer components (Chen et al. 2006, Fu et al. 2007, Hartmann et al. 2010, Wang and Chen 2010, Bell et al. 2014). However, our dynamic scenario analysis further extended knowledge of how silvicultural intensity, combined with rotation age, and harvest method, impacted the profit from boreal forest stands, as explained in the following sections.

Table 3.3. Silvicultural costs ($/ha, 2016) of silvicultural intensities.

Original forest type	**Desired forest type**	**Silvicultural intensity**	**Treatment regime** [a]	**% of sites treated**	**Costs ($/ha)**	**Total costs ($/ha)**
			Natural	100%	0.00	
			Slash pilling	80%	19.00	
			Slash burning	80%	14.30	
			Direct costs	100%	16.80	
B	B	No	Overhead/administration	10% [c]	10% of the costs of all treatments	47.78
			Natural	100%	0	
			Slash pilling	80%	19.00	
			Slash burning	80%	14.30	
			Direct costs	100%	16.80	
M	B	No	Overhead/administration	10% [c]	10% of the costs of all treatments	47.78
			Natural	100%	0.00	
			Slash pilling	80%	19.00	
			Slash burning	80%	14.30	
			Direct costs	100%	16.80	
C	B	No	Overhead/administration	10% [c]	10% of the costs of all treatments	47.78
			MSIP	100%	155.00	
			Plant	100%	432.70	
			Ctend	200%[b]	123.55	
			Slash pilling	80%	19.00	
			Slash burning	80%	14.30	
			Direct costs	100%	16.80	
B	M	High	Overhead/administration	10% [c]	10% of the costs of all treatments	1119.73
			MSIP	50%	155.00	
			Plant	100%	432.70	
			Ctend	60%	123.55	
			Slash pilling	80%	19.00	
			Slash burning	80%	14.30	
			Direct costs	100%	16.80	
M	M	Low	Overhead/administration	10% [c]	10% of the costs of all treatments	690.55
			MSIP	100%	155.00	
			Plant	100%	432.70	
C	M	Low	Ctend	60%	123.55	

			Slash pilling	80%	19.00	
			Slash burning	80%	14.30	
			Direct costs	100%	16.80	
			Overhead/administration	10% [c]	10% of the costs of all treatments	775.8
			MSIP	100%	155.00	
			CSIP	100%	139.70	
			Plant	100%	432.70	
			Ctend	200% [b]	123.55	
			Slash pilling	80%	19.00	
			Slash burning	80%	14.30	
			Direct costs	100%	16.80	
B	C	High	Overhead/administration	10% [c]	10% of the costs of all treatments	1119.73
			MSIP	100%	155.00	
			Plant	100%	432.70	
			Ctend	100%	123.55	
			Slash pilling	80%	19.00	
			Slash burning	80%	14.30	
			Direct costs	100%	16.80	
M	C	High	Overhead/administration	10% [c]	10% of the costs of all treatments	830.16
			MSIP	100%	155.00	
			Aerial seed	100%	106.13	
			Ctend	40%	123.55	
			Slash pilling	80%	19.00	
			Slash burning	80%	14.30	
			Direct costs	100%	16.80	
C	C	Low	Overhead/administration	10% [c]	10% of the costs of all treatments	389.39

[a] Treatment regime: MSIP – mechanical site preparation, CSIP – chemical site preparation, Ctend – chemical tending.

[b] 200% means applying chemical tending twice.

[c] A 10% overhead cost was added to offset managerial and administrative costs.

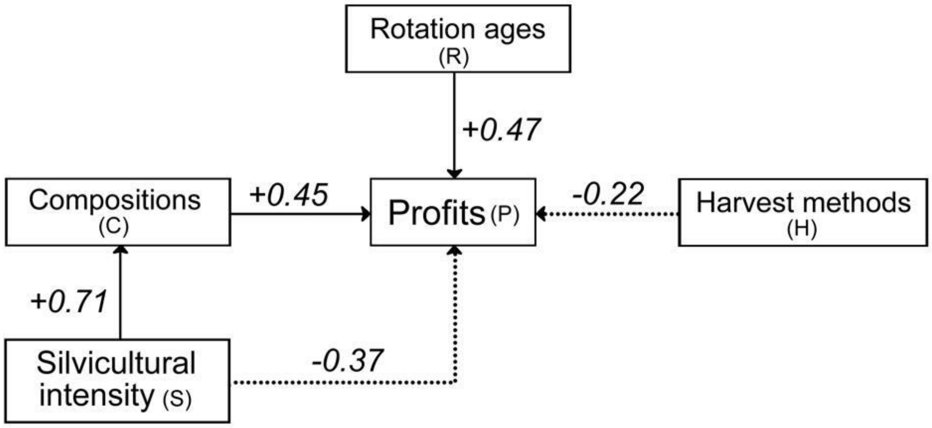

Figure 3.5. Direct relationships among profits and silvicultural intensity, compositions, rotation ages, and harvest methods. The coefficients are standardized prediction coefficients alongside each path. Solid lines represent positive significant effect ($P \leq 0.001$), and dotted lines represent negative significant effect ($P \leq 0.001$).

3.4.2 Gross total volume and net merchantable volume

The results of GTV and NMV in different forest compositions using different rotation ages and harvesting methods in the boreal forests are shown in Table S1. We found that rotation age had a significant effect on GTV ($P < 0.001$), which is high in young forests, peaks at intermediate ages, and is lowest in the late-successional stage (Figure 3.6). These results are consistent with previous studies (Hember et al. 2012, Zhang and Chen 2015). However, those studies focused only on the impact of rotation ages on above ground biomass, whereas our study not only focused on the GTV but also included forest composition as one of the variables. We found that GTV differed among forest compositions in natural boreal forests ($P < 0.001$), which is highest in broadleaf stands, followed by mixedwood and coniferous stands (Figure 3.6). This difference is due to the fact that broadleaved species, such as trembling aspen, are shade intolerant and generally grow faster than coniferous species with more volume in the stem exclusion stage after disturbances (Chen and Luo 2015), while mixedwood is likely to be more productive, primarily in terms of biomass, than monocultures, since polycultures can increase resource use and nutrient retention via niche differentiation or partitioning and interspecies facilitation (Yachi and Loreau 1999, Loreau et al. 2001, Knoke et al. 2008, Zhang and Chen 2015). Previous studies also found that species diversity in polycultures may show no significant relationship to aboveground productivity because of limited variation in productivity among sample plots and measurement error on individual samples, as well as scale variations (Guo and Ren 2014).

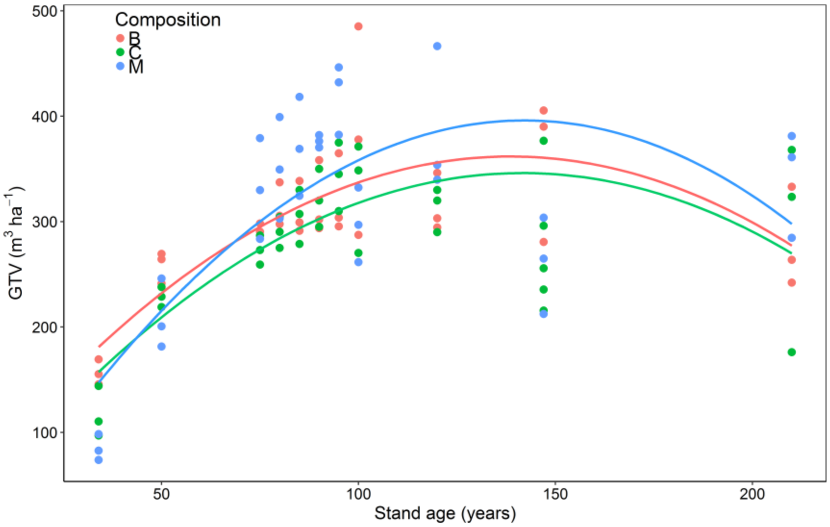

Figure 3.6. Gross total volumes (m^3/ha) of broadleaved, mixedwood, and coniferous stands change with rotation ages. Overstory types: B – broadleaf, C – conifer, and M – mixedwood.

Similar trends were observed for NMV to those reported for GTV. Both rotation age ($P < 0.001$) and forest composition ($P < 0.001$) significantly affected NMV, whereas harvest method had a marginal significant effect (P < 0.1) on NMV (Figure 3.7). NMV peaked at intermediate ages and was lower in the late-successional stage, similar to GTV (Plonski 1981, Saunders and Arseneault 2013). NMV in broadleaved stands was higher in the stand initialization than followed by mixedwood and coniferous stands, and mixedwood stands generated significantly more NMV (8.6%) than coniferous stands. We applied different wood fibre recovery factors for broadleaved and coniferous species that converted GTV to NMV (Ride 2001), which explained the difference.

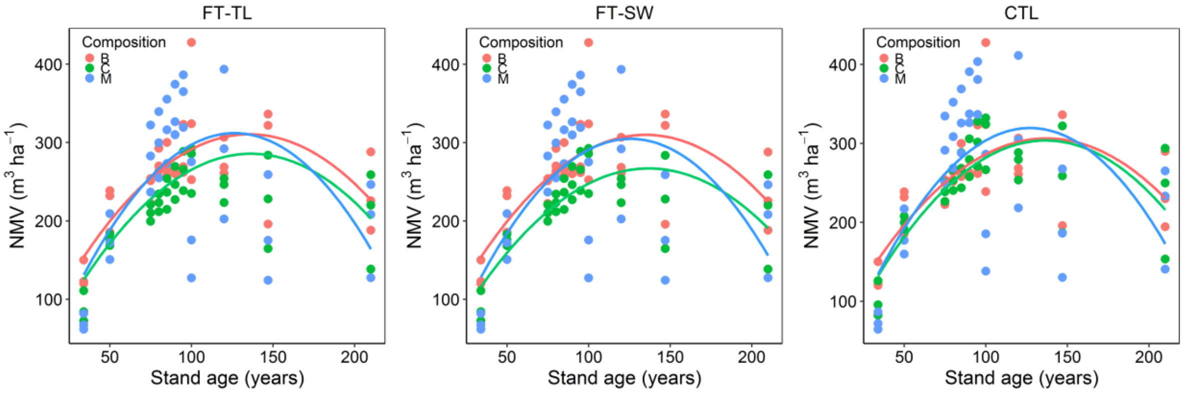

Figure 3.7. Net merchantable volume (m^3/ha) of broadleaved, mixedwood, and coniferous stands change with rotation ages using FT-TL (Full-Tree to Roadside Tree-Length-to-Mill), FT-SW (Full-Tree to Roadside Shortwood-to-Mill), and CTL (cut-to-length) harvest methods. Overstory types: B – broadleaf, C – conifer, and M – mixedwood.

3.4.3 Silvicultural costs and profits

The silvicultural costs ($/ha) differed with silvicultural intensity (Table 3.3). We considered silvicultural costs < $100/ha as no silviculture, low silvicultural intensity with silvicultural costs between $100/ha - $800/ha, and high silvicultural intensity with silvicultural costs > $800/ha. The results of dynamic scenario analysis showed that forest composition had positive effects on profit, silvicultural intensity and harvest methods had negative effects on profit, while rotation ages had a quadratic relationship with profit (Figure 3.5). Profit was significantly directly influenced by silvicultural intensity (-0.37, $P < 0.001$), rotation age (+0.47, $P < 0.001$), forest composition (+0.45, $P < 0.001$) and harvest method (-0.22, $P < 0.001$), and profit was also indirectly influenced by silvicultural intensity by affecting forest composition (+0.32, $P < 0.001$). Therefore, the net total effect of silvicultural intensity on profit was negative (-0.05).

The negative total effect of silviculture on profit is consistent with the result of a previous study that reported intensive silviculture demanded a higher upfront investment that negatively affected profits (Rodrigues 1998, Anderson and Luckert 2007), because when silvicultural investment increases (higher intensity), the cost increases and the profit decreases. However, some findings indicated that intensive management increases economic performance through increasing productivity and stocking volume (Yin and Sedjo 2001, Rojo et al. 2005, Griess et al. 2012, Armstrong 2014, Biber et al. 2015, Petrokofsky et al. 2015). These conflicting results may arise from the types of forests considered, forest compositions, rotation ages, major technical change and harvesting methods implemented in the forest management.

Silvicultural intensity influences profit by facilitating the objectives in forest composition, which often include higher conifer components (Soalleiro et al. 2000, Montigny and MacLean 2006, Saunders and Arseneault 2013). In our study, profits of coniferous stands were on average highest among all forest compositions, followed by mixedwood and broadleaved stands in boreal forests. Another study also found that with an increase in the proportion of coniferous species, there was an increase in profits, because lumber and softwood market pulp made from coniferous species had higher economic value than the products made from broadleaved species (Montigny and MacLean 2006). However, broadleaved species can increase quality and volume of biomass in conifer-dominated stands (Legare et al. 2005a). For commercial management, admixtures of less profitable broadleaved trees to profitable conifers may achieve a greater economic utility, only if the more economic value is obtained from broadleaved species such as white birch and trembling aspen. Mixed-species forests will be more attractive for a risk-averse manager of forest resources because polycultures are better able to endure disturbances than monocultures (Knoke et al. 2008, Griess et al. 2012). However, mixedwood stands have higher harvesting costs per unit volume due to demand for higher harvester skill levels and logistical difficulties in operations than monocultures (Paquette and Messier 2009, Royer-Tardif and Bradley 2011).

Profit was highest at intermediate rotation ages, and was lower in older rotation ages in coniferous stands using FT-TL and CTL. The profits in mixedwood stands increased rapidly using FT-TL and FT-SW, and increased with rotation age initially but decreased at late-succession stage using Cut-to-Length method (CTL) (Figure 3.8). The preference for longer rotations with higher fibre recovery meant that individual trees could be harvested when profit is the highest corresponding to the highest percentage of saw logs (Knoke 2012). However, aging increases tree mortality and decreases growth of net biomass (Luo and Chen 2011, Pretzsch et al. 2014, Chen et al. 2016a). Although a 125-year rotation generates more volume with optimal ecological benefits in boreal forests (Erickson et al. 1999), it may also result in decayed wood that has lower merchantable volume with lower economic value (Willcocks 1997). Meanwhile, shorter rotations of 50 and 75 years are unlikely to achieve maximum economic gains. Therefore, the 100-year rotation age is the optimum within the recommended rotation ages in our study (50, 75, 80, 85, 90, 95, 100, 125 years), and is also the target rotation age recommended in Ontario. Yet it remains uncertain how economic activities might best maintain and support multiple ecological functions and associated services in the boreal forests (Chen et al. 2016b). Stands with longer rotation ages accumulate more soil organic matter and litter, and provide more non-commercial benefits such as biodiversity conservation (Harmon and Marks 2002, Luckert and Williamson 2005, Thompson et al. 2009). It is important to anticipate the long-term effects of forest management alternatives on economic gains as well as ecological functions and services of forest ecosystems. Therefore, we need to consider the trade-offs between economic gains and ecological losses in the boreal forests in further studies.

As for the harvest method, profit was higher using FT-TL method than FT-SW, followed by CTL (Figure 3.8, Table S2). The corresponding costs (FT-TL < FT-SW< CTL) also negatively affected profit. CTL equipment is very expensive and requires significant training to operate and maintain, and it is probably only cost efficient in pure coniferous stands (Favreau and Corneau 1998). Most of the logging systems in northwestern Ontario are feeding both sawmills and pulp mills, and are working in mixedwood. Although the CTL system provides a higher yield of green merchantable wood per cubic meter, the average economic gain from the products produced using FT was higher when working in mixedwood (Favreau 1997, Plamondon and Pagé 1997). Thus, due to increasing economic potential of forest residues through a better suited FT harvesting system at lower harvesting costs, forest harvesting in the boreal forest has changed from CTL to FT system over the last decade (Miettinen et al. 2014, Melendez 2015). FT harvest systems tend to better utilize all the

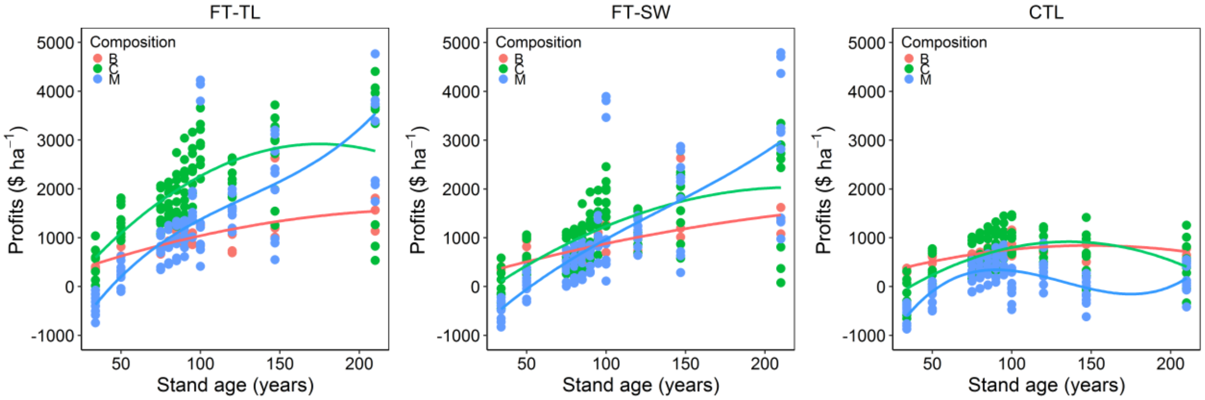

Figure 3.8. Profits of broadleaved, mixedwood, and coniferous stands change with rotation ages using FT-TL (Full-Tree to Roadside Tree-Length-to-Mill), FT-SW (Full-Tree to Roadside Shortwood-to-Mill), and CTL (cut-to-length) harvest methods.

materials coming from harvesting operations, including tops, branches, and bark for hog fuel. However, compared to conventional CTL, there are possibly more negative impacts of the incremental removal of tops and branches on soil nutrients, soil carbon, forest and soil productivity, water availability, biodiversity, microclimate, and air, microbial activity, all of which negatively affect subsequent tree growth and economic gains (Johnson and Curtis 2001, Lattimore et al. 2009, Walmsley et al. 2009, Nave et al. 2010, Thiffault et al. 2011, Hume et al. 2017). Therefore, there are trade-offs between economic gain and ecological losses using different harvest methods.

As expected, there were notable differences in profits from different forest management alternatives. We show evidence that silvicultural intensity, forest composition, rotation age and harvesting method significantly affected economic gains. Moreover, we found that the maximum profit of $3305 /ha was achieved within recommended rotation ages (50, 75, 80, 85, 90, 95, 100, 125 years) in the following forest management scenario: applying low silvicultural intensity to the original conifer forest to continue generating the coniferous stands, harvesting the fibre at a reference rotation age of 100 years, and using the FT-TL harvesting method (Table S2). Our results add a new and important understanding of the combined economic effects of varying silvicultural intensities, forest compositions, rotation ages and harvesting methods associated with forest management alternatives in boreal forests.

3.5 Conclusions

Timber production and economic gains are important forestry objectives. This study represents the first empirical evidence for a series of forest management alternatives that explores the impact of varying silvicultural intensities, forest compositions, rotation ages, and harvest methods on GTV, NMV, and profit in boreal forest management. Our results can help in developing and implementing strategies on forest investment, timber supply, land use, and for sustainable forest management that can jointly produce economic gains and other ecological functions and ecosystem services.

There are some limitations of this study. Firstly, our analyses were limited by the assumptions including the conversion factors and the wood fibre recovery factors. Secondly, we considered white birch having only biomass value, but it could be used for value-added products including furniture, plywood, oriented strand board, flooring and birch syrup. Thirdly, this research has been limited both spatially and temporally, because transportation costs for individual stands were not differentiated, and the results are sensitive to the prices of forest products, the costs of silviculture, harvesting, processing, transportation, and production used in calculating the values of profits along with the rotation age, which might change with time. Finally, in our analysis, we did not consider ecological losses or social costs associated with natural disturbances such as wildfire and climate change. Further research should focus on the economic analysis of forest management alternatives in spatial landscape analysis and consider economic and ecological trade-offs since the economic gain is only one part of forest management objectives.

CHAPTER 4: TRADE-OFFS AND SYNERGIES BETWEEN ECONOMIC GAINS AND PLANT DIVERSITY ACROSS A RANGE OF MANAGEMENT ALTERNATIVES IN BOREAL FORESTS

4.1 Abstract

Intensive forest management activities that maximize economic gains could have a negative impact on the ecosystems and generate land use and environmental conflicts, which may, in turn, translate to poor delivery of ecosystems services. Although plant diversity is positively associated with multiple ecosystem functions, it remains unclear how economic gains from forest management influence plant diversity across a diverse range of vegetation strata. We analyzed the relationships between economic gains, assessed as profit, and plant species richness following a range of forest management alternatives (managing rotation age and overstorey composition) for the boreal forests of Canada. We found a hump-shaped relationship between total plant species richness and profit, with total plant species richness increasing initially, reaching a peak, and then declining with increasing profits. The relationship between profit and plant diversity differed among vegetation strata. Understorey plant species richness followed similar trends to total plant species richness, but overstorey tree species richness increased linearly with profit. The results of path analysis presented forest management alternatives as major drivers determining profit and plant diversity across vegetation strata. Our analysis indicated that maximum profit ($5000/ha) could lead to 20% loss of total plant species richness, while total plant species richness could be maximized by giving up 54% of the profit. Among the alternatives we compared, we conclude that

managing for mixedwood with approximately a rotation of 100 years is an optimal compromise between economic and plant diversity objectives.

4.2 Introduction

Forest ecosystems provide a diverse range of ecological functions and services to humanity (Millennium Ecosystem Assessment 2005). As one of the world‘s most important biogeoclimatic regions (Bradshaw et al. 2009), boreal forests contribute approximately 45% of the global growing stock of timber, fiber, and bioenergy (Vanhanen et al. 2012). However, forest management intensification that maximizes economic gains may result in the loss of habitat and biodiversity (Foley et al. 2005, Monkkonen et al. 2014, Frank and Schlenker 2016). Others, however, have reported synergic (Rana et al. 2017) or lack of relationship (Steffan-Dewenter et al. 2007, Clough et al. 2011) between forest biodiversity and economic gains. Across a wide range of management alternatives, the relationships between biodiversity and economic gains tend to be nonlinear (Chan et al. 2006, Steffan-Dewenter et al. 2007). Understanding these potentially nonlinear relationships would help choose management options with limited or no ecological losses while still satisfy economic gains. In boreal forests, economic gains are strongly determined by management intensification involving changes in rotation age and overstorey composition (Chen et al. 2017). However, the relationships between economic gains and plant diversity following forest management alternatives across a diverse range of vegetation strata remain poorly understood.

Plant species diversity is positively linked with multiple ecosystem functions such as the provision of habitat, nutrient cycling, energy flow, and regulating succession (Wardle et al. 2004, Royo and Carson 2006, Cardinale et al. 2012, Gamfeldt et al. 2013). Species richness is the most important measure of diversity because each species provides unique ecosystem functions and services (Hector and Bagchi 2007). Overstorey tree species composition not only determines the economic value of forest products (Mathey et al. 2009), but also influences understorey diversity through availability and variability of resources such as light and soil nutrients (Hart and Chen 2006, Barbier et al. 2008, Reich et al. 2012, Kumar et al. 2017b). Although accounting for a small fraction of total ecosystem biomass, understorey vegetation including shrub, herb, bryophyte, and lichen species contributes substantially to total forest plant diversity and a variety of ecosystem functions (Nilsson and Wardle 2005, Gilliam 2007, Gilliam and Roberts 2014, Zhang et al. 2017).

Forest management alternatives for the boreal forest, including different rotation ages and overstorey tree species composition goals, affect economic gains (Chen et al. 2017), as well as plant diversity (Hart and Chen 2008, Bartels and Chen 2015, Bartels et al. 2017, Kumar et al. 2018). The choice of rotation age influences the economic value of product mix, because biomass available for harvest tends to increases with rotation age (Liski et al. 2001, Asante and Armstrong 2012). However, extending the rotation age may not be economically optimal because aging can result in tree mortality and lower net biomass production (Luo and Chen 2011, Chen and Luo 2015). On the other hand, plant diversity also tends to increase initially with increasing stand age, as vegetation requires time to colonize the available resources following disturbances; declines in plant diversity in older stands occur as a result of reduced resource availability and increased interspecific competition (Grime 1973, Reich et al. 2012). However, plant diversity and stand age relationships could also differ among plants of different life history traits, or between vascular and non-vascular plants (Hart and Chen 2006, 2008, Kumar et al. 2017b).

Similarly, overstorey species composition (broadleaf, mixedwood, and conifer) — often regulated by regeneration method (natural or artificial) at the stand initiation stage — affects economic gains (Chen et al. 2017), as well as plant diversity (Barbier et al. 2008, Hart and Chen 2008, Kumar et al. 2017b). Economic gains differ due to the resultant forest products mix of broadleaf and conifer species because the products made from coniferous wood generally have better market value in the Canadian forest sector than those made from broadleaved wood (Chen et al. 2017). On the other hand, the relative proportion of broadleaved and coniferous trees in the overstorey may also affect plant diversity in the understorey as a result of different resource conditions (light and nutrient availability) (Barbier et al. 2008, Bartels and Chen 2010, 2013, Kumar et al. 2017b). An increased conifer proportion would decrease the overstorey and shrub plant diversity, or vascular plant diversity, because of less resource availability (Hart and Chen 2006, Barbier et al. 2008). However, an increased conifer proportion would increase non-vascular species diversity because coarse woody debris and thick forest floor layer in coniferous stands favor the establishment of mosses and lichen species (Legare et al. 2005b, Startsev et al. 2008, Bartels and Chen 2013).

Although previous studies have tested the effect of stand age and overstorey composition on economic gains (Chen et al. 2017) and understorey plant diversity (Reich et al. 2012, Kumar et al. 2017b), how forest management driven-economic gains influence plant diversity across diverse vegetation strata remains unclear. This study aims to examine the relationships between economic gains and plant diversity given different forest management alternatives and across vegetation strata in boreal forests. Specifically, we address (i) how forest management alternatives (managing rotation age and overstorey composition) affect profit; (ii) how forest management alternatives affect plant diversity across vegetation strata; and finally (iii) how the relationships (trade-offs or synergies) between profit and plant diversity vary across the range of forest management alternatives and vegetation strata.

4.3 Methods

4.3.1 Study area and chronosequence data

Our study was conducted in the boreal forest region, approximately 150 km north of Thunder Bay, Ontario, Canada, between 49°44′ to 49°65′ N and 89°16′ to 90°13′ W. This area is characterized by warm summers and cold, snowy winters. Mean annual temperature is 1.9 ºC and mean annual precipitation is 824.8 mm as measured by the closest meteorological station in Cameron Falls, Ontario, Canada (Environment Canada 2016). Dominant tree species in order of shade tolerant from least to most, include jack pine (*Pinus banksiana* Lamb.), trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh), black spruce (*Picea mariana* (Mill) B.S.P.), white spruce (*Picea glauca* (Moench) Voss), and balsam fir (*Abies balsamea* (L.) Mill.). Soils in our study area largely deposited by the Wisconsinan glaciation, which ended approximately 9,500 years ago in this region. Stand-replacing wildfire is the dominant natural disturbance in the study area, with an average fire-return interval of approximately 100 years, resulting in a mosaic of stand ages in the area (Senici et al. 2010). There has been a 40-year history of commercial logging with full-tree and stem-only harvest methods in the study area (Shrestha and Chen 2010).

We used a replicated chronosequence design that covered a wide range of empirical stands in age classes: 8-, 34-, 99-, 147- and 210-year on mesic sites (Table 4.1), representing the stand initiation, stem exclusion, early canopy transition, late canopy transition, and gap

Table 4.1. Characteristics of the 45 sample stands in the boreal forests of Ontario, Canada.

			Stand density (stems ha^{-1})	Stand composition (%)[c]					
Stand age	Overstorey[a]	N	or basal area (m^2 ha^{-1})[b]	Trembling aspen	White birch	Jack pine	Spruce spp.	Balsam fir	Others
8	B	3	5933 (581)	95 (5)		5 (5)			
	C	3	7067 (1551)	3 (3)		97 (3)			
	M	3	6933 (926)	45 (9)		55 (9)			
34	B	3	26 (1)	93 (3)	4 (4)	1 (1)	1 (1)		1 (1)
	C	3	28 (2)	4 (2)		95 (3)	1 (1)		
	M	3	13 (1)	52 (4)		41 (6)	7(5)		
99	B	3	51 (7)	91 (2)	3 (2)		2 (2)	1 (1)	4 (1)
	C	3	52 (2)	3 (2)		43 (12)	50 (17)	4 (3)	
	M	3	43 (5)	40 (12)	16 (11)	10 (6)	15 (8)	18 (3)	2 (1)
147	B	3	58 (8)	85 (3)	7 (4)		5 (1)	2 (1)	1 (1)
	C	3	51 (9)	1 (1)	2 (2)	53 (27)	37 (26)	7 (1)	
	M	3	35 (1)	45 (6)	21 (8)		10 (3)	23 (4)	2 (2)
210	B	3	41 (3)	54 (22)	24 (18)		10 (6)	10 (4)	2 (1)
	C	3	40 (8)	5 (5)	7 (4)		36 (18)	50 (17)	2 (1)
	M	3	46 (3)	11 (4)	39 (5)	5 (3)	38 (7)	7 (3)	

Notes: [a] Overstorey types: B = broadleaf, C = conifer, M = mixedwoods.

[b] Values are means with 1 SE in parentheses. Stand density (stems ha^{-1}) was determined for the younger (8 years old) stands and basal area (m^2 ha^{-1}) for older stands.

[c] The ‗Others‘ category includes *Salix* spp. and *Prunus pensylvanica,* which were not considered commercial species in our study.

dynamic stages of boreal forest development, respectively (Chen and Popadiouk 2002). Stand age for each plot was determined according to records of the last stand-replacing fire and by coring three dominant/co-dominant trees of each tree species inside or near the plot (Hart and Chen 2008). Following the methods described in Senici et al. (2010), stand age was the average of ring counts from the tree samples of the species with the oldest age. For stands younger than 70 years, detailed fire records were available. Within each of the selected mature (≥ 34 years) stands, we established a randomly located 0.04 ha (11.28 m radius) fixed-area circular plot, located > 50 m from the forest edge, to represent the stand (Luo and Chen 2015). For young (8-year-old) stands, tree stems were counted by species within three randomly located circular subplots, each 0.005 ha (3.99 m radius) within the large 0.04 ha plot. The stands were allocated several kilometers apart to ensure that the sampled stands were interspersed and spatial autocorrelation and edge effects were minimized (Legendre and Legendre 1998).

4.3.2 Plant species richness

For simplicity, we focused on reporting plant species richness as the measure of diversity because each species contributes uniquely to ecosystem functions according to the singular hypothesis (Naeem 2002). Within each 0.04 ha plot, we surveyed plant species richness separately for overstorey trees, shrubs, other vascular plants, and all non-vascular species based on vertical strata. We defined trees in the 0.04 ha plot as stems with height ≥ 1.3 m. Separate counts of small trees with height ≥ 1.3 m and diameter at breast height (DBH) in the range of 3–9 cm were made in a 0.005 ha circular subplot centered in the 0.04 ha plot. Overstorey type was assigned based on the percentage of stem density and basal area of broadleaf and conifer tree species for young and mature stands, respectively. Broadleaved and coniferous stands were defined as having > 65% broadleaved or coniferous tree species by basal area, while all other stands were classified as mixedwood stands (Hume et al. 2016).

Understorey vegetation surveys were conducted during the period of peak vegetation cover in July-August 2016, following Canada's National Forest Inventory Ground Sampling Guidelines. Plants in the shrub stratum, understorey vascular plant stratum, and non-vascular species stratum were assessed by species by visually estimating the percent cover within a circular 0.04 ha plot (Mueller-Dombois and Ellenberg 1974). The shrub stratum included any woody stem with a height between 1.3 and 4.0 m (Hart and Chen 2008); a species found in the shrub stratum could also be present in the herb stratum. The vascular plant stratum included all stems < 1.3 m height, including woody plants, forbs, graminoids, clubmosses, and ferns. The non-vascular species stratum consisted of terrestrial bryophytes (i.e., mosses and liverworts) and lichens. All plants were identified to the species level (for further details, see Kumar et al. (2017b)).

4.3.3 Forest management alternatives

In order to examine the economic gain-plant diversity relationship as it relates to decisions on rotation age, we first applied regression estimates using empirical data of stand ages (i.e., 8-, 34-, 99-, 147- and 210-year) to interpret the plant species richness of overstorey, shrub, vascular, and non-vascular species strata at a variety of rotation ages. Total plant species richness was the sum of the richness across those four vegetation strata. A set of alternative rotation ages were projected based upon common practices in the study area: 50 years as the ecologically and biologically acceptable minimum rotation, 75 years as the operational rotation age under tenure, 100 years as recommended by law in Ontario, and 125 years as the rotation associated with maximum volume accumulation and optimal ecological benefits in boreal forests (Willcocks 1997). We also extended the alternative rotation ages between the 75- and 100-year rotations to include 80-, 85-, 90-, and 95-year rotations, because financial returns are typically highly sensitive to minor differences in rotation ages. Then we used Forest Vegetation Simulator (FVS$^{\text{Ontario}}$) to project gross total volume for economic gains at each of the various rotation ages based on current size and calibrated values of empirical stand conditions (Woods and Robinson 2007). Existing inventory conditions of 34-year old stands were used to project volumes of rotation ages of 50, 75, 80, 85, 90, and 95 years, while empirical data from 99-year stands were used to project volume of rotation ages of 100 and 125 years in FVS$^{\text{Ontario}}$. We used rotation age for the economic gains and trade-off analysis, while stand age is used to describe the plot data. We used the proportion of conifer tree species (i.e., jack pine, white spruce, black spruce and balsam fir) as a continuous variable to represent overstorey composition in each empirical case, as well as in simulated stands, expressed as a percentage of the total basal area. Generally, intensive forest management results in a higher proportion of conifer tree species in the overstorey (Chen et al. 2017).

4.3.4 Economic gains

We assumed that all prices of forest products and costs of silviculture, harvesting, processing, transportation, and ―all-in" delivered costs (i.e., production, shipping, distribution, and administrative expenses) were constant and were happening at the same time (year 2016). This assumption was necessary because costs and benefits will both change over time. We calculated the gross total volume of stands in each management alternative using Honer‘s equations (Honer 1983). The gross total volume was then converted into net merchantable volume based on wood fibre recovery factor of Full-Tree to Roadside Tree-Length-to-Mill harvest method (i.e., 82.1%) from fibre utilization research in Northern Ontario and the

Scaling Manual for clearcut operations (Ride 2001). The economic gains, assessed as profit for each forest management alternative for each empirical or simulated plot with different rotation ages were then calculated by subtracting the present costs from present benefits of the six forest product assortments (i.e., lumber, softwood market pulp, hardwood market pulp, newsprint, hog fuel, and pellets) produced per hectare (for further details, see Chen et al. (2017).

4.3.5 Statistical analysis

Generalized additive models (GAM) were used to estimate the effects of rotation age and overstorey composition on profit and plant diversity. GAM integrates smooth functions to model non-linear relationships between covariates and dependent variables (Rose et al. 2012). The effect of profit on plant diversity across vegetation strata was analyzed by simple or polynomial regression. We selected the best relationships based on Akaike Information Criterion (AIC); the most parsimonious model was selected when the difference in AICs between alternative models was < 2 (Burnham and Anderson 2002). We tested the assumption of normality using Shapiro–Wilk‘s test, and that of homogeneity of variance using Bartlett‘s test. If normality or homogeneity was not achieved, we bootstrapped the estimates of regression coefficients by using the _*boot*‘ package in R with 4,999 iterations to generate 95% confidence intervals (Adams et al. 1997).

We used path analysis to link multivariate relationships between forest management alternatives, profit, and plant diversity across vegetation strata. We first examined the bivariate relationships between each causal path. We fit each pair of variables using simple linear or second-order polynomial regression. We reported the significant relationships as linear or polynomial. We examined the assumptions of normality of homogeneous variance by Shapiro-Wilk‘s test and Bartlett‘s test, respectively, and these tests confirmed the assumptions were met for all analyses. The path analysis was implemented using the *lavaan* package (Rosseel 2012). All analysis was conducted in R version 3.4.3 (R Development Core Team 2017).

4.4 Results

4.4.1 Effects of rotation age and overstorey composition on profit and plant diversity

Both rotation age and overstorey composition significantly influenced profit ($P < 0.001$; Figure 4.1). Profit increased linearly with rotation age for mixedwood stands but increased and reached a maximum at approximately 125 and 175 years for coniferous and broadleaved stands, respectively. Profit did not differ between coniferous and mixedwood stands, but both of these composition types offered higher profit than did broadleaved stands from intermediate to late rotation ages.

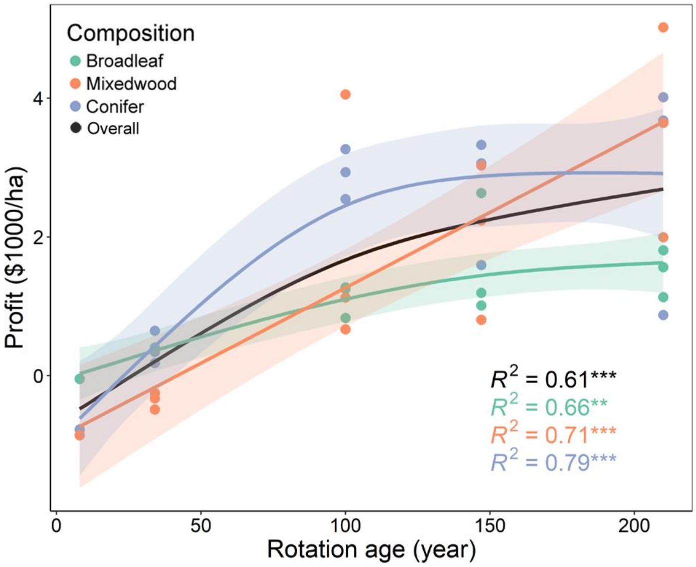

Figure 4.1. Trends in changing profits with rotation age and overstorey composition. The lines indicate smooth functions of the best model fit for the long-term trends using general additive models (GAM). Shaded regions are the approximate 95% confidence intervals. R^2 values indicate the model fit. Significant differences ($\alpha = 0.05$). Significant codes (p-value): 0 _***‘, 0.001_**‘, 0.01_*‘.

Total plant species richness increased with stand age, reached a maximum at intermediate ages, and decreased thereafter (Figure 4.2A). Total plant species richness was on average higher in mixedwood than broadleaved and coniferous stands at ages between 75 and 125 years. The effects of stand age and overstorey composition on plant species richness differed among vegetation strata. Stand age did not affect overstorey tree species richness and shrub richness in any of three overstorey types, but mixedwood stands on an average had higher overstorey richness than the other two stand types (Figure 4.2B). Mixedwood and broadleaved stands had higher shrub richness than coniferous stands at ages between 100 and 150 years (Figure 4.2C). The understorey vascular plant species richness followed a similar pattern to that of total plant species richness but increased again in the late successional stage (Figure 4.2D). Vascular plant richness was relatively higher in mixedwood and broadleaved stands than coniferous stands at ages between 50 and 125 years (Figure 4.2D). Non-vascular species richness on average reached a maximum at around 50 years, decreased from 50 to 100 years, increased again to 150 years, then decreased thereafter (Figure 4.2E). Non-vascular species richness in coniferous stands followed a similar pattern to the overall trend, but in mixedwood stands, non-vascular species richness reached a maximum at 50 years followed by a decline. Mixedwood and coniferous stands on average had higher non-vascular species richness than did broadleaved stands (Figure 4.2E).

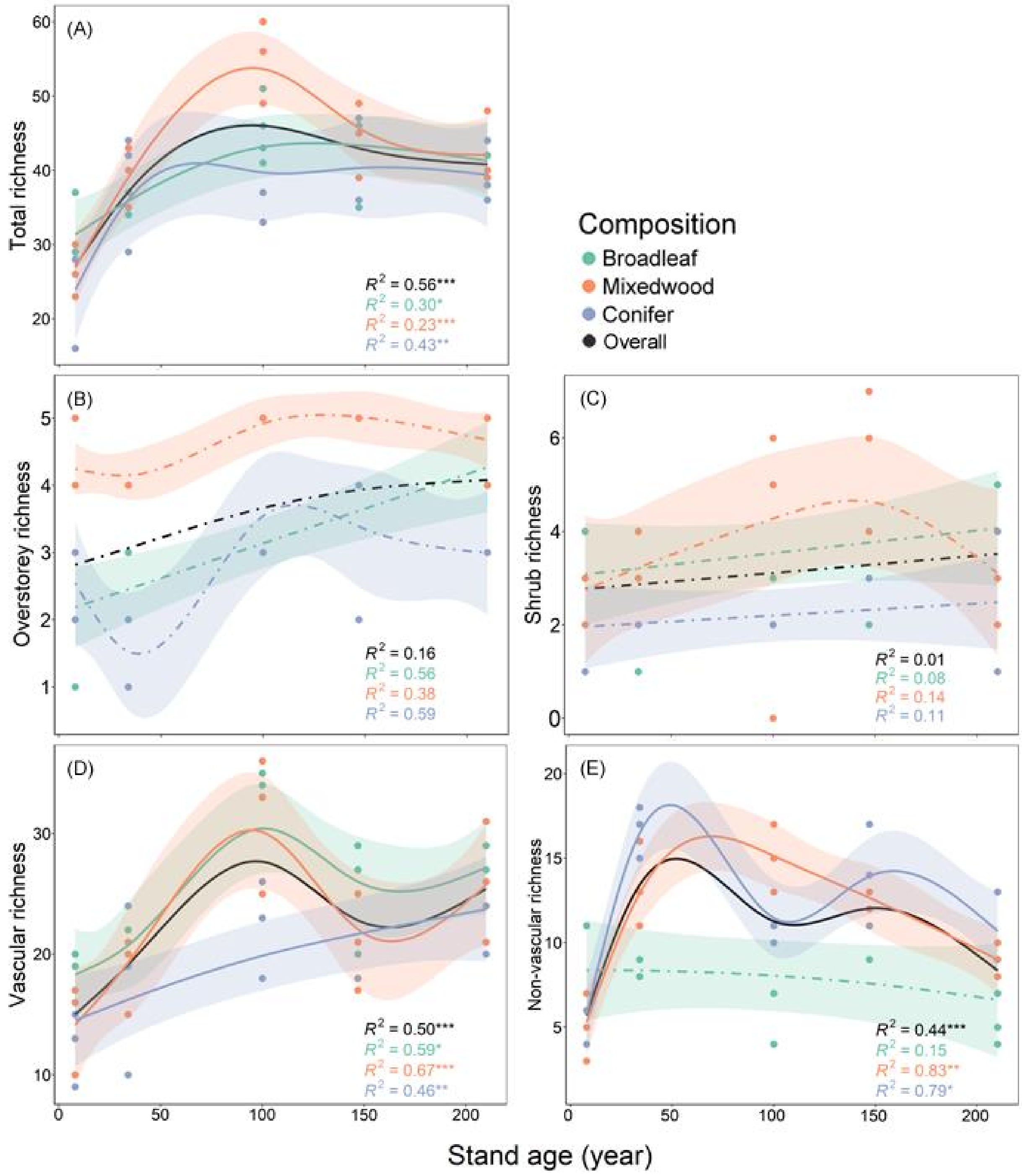

Figure 4.2. Trends in total plant richness and richness of overstorey, shrubs, and vascular and non-vascular species with rotation age and overstorey composition. The lines indicate smooth functions of the best model fit for the long-term trends using general additive models (GAM). Solid lines represent statistically significant trends while dashed lines show the insignificant trends. Shaded regions are the approximate 95% confidence intervals. R^2 values indicate the model fit. Significant differences (α = 0.05). Significant codes (p-value): 0 _***‘, 0.001_**‘, 0.01_*‘.

4.4.2 Relationship between profit and plant diversity

Economic gains associated with the different forest management options, assessed as profit, significantly ($P < 0.001$) affected total plant species richness, which increased with increasing profit, reached a peak of 45 species at a $2300/ha profit and decreased thereafter (Figure 4.3A). If the management decision was to maximize profits ($5000/ha), only 80% of the peak total plant richness (36 species) could be achieved. Total plant species richness peaks differ among overstorey types, with mixedwood stands on average having higher richness than broadleaved and coniferous stands for a given level of profit. A peak of 51 plant species occurred at a profit of $2500/ha in mixedwood stands, 45 species at a profit of $1800/ha in broadleaved stands, and 41 species at a profit of $2500/ha in coniferous stands.

The effect of profit on richness also differed among individual vegetation strata. With increasing profit, richness in the overstorey, the main vegetation stratum contributing to economic gains, increased linearly ($P < 0.001$), and mixedwood stands had on average higher overstorey richness than broadleaved and coniferous stands (Figure 4.3B). Profit had convex relationships with the richness of shrub, vascular and non-vascular species strata, where species richness increased with increasing profits, reached peaks, and decreased thereafter (Figures 4.3C-E).

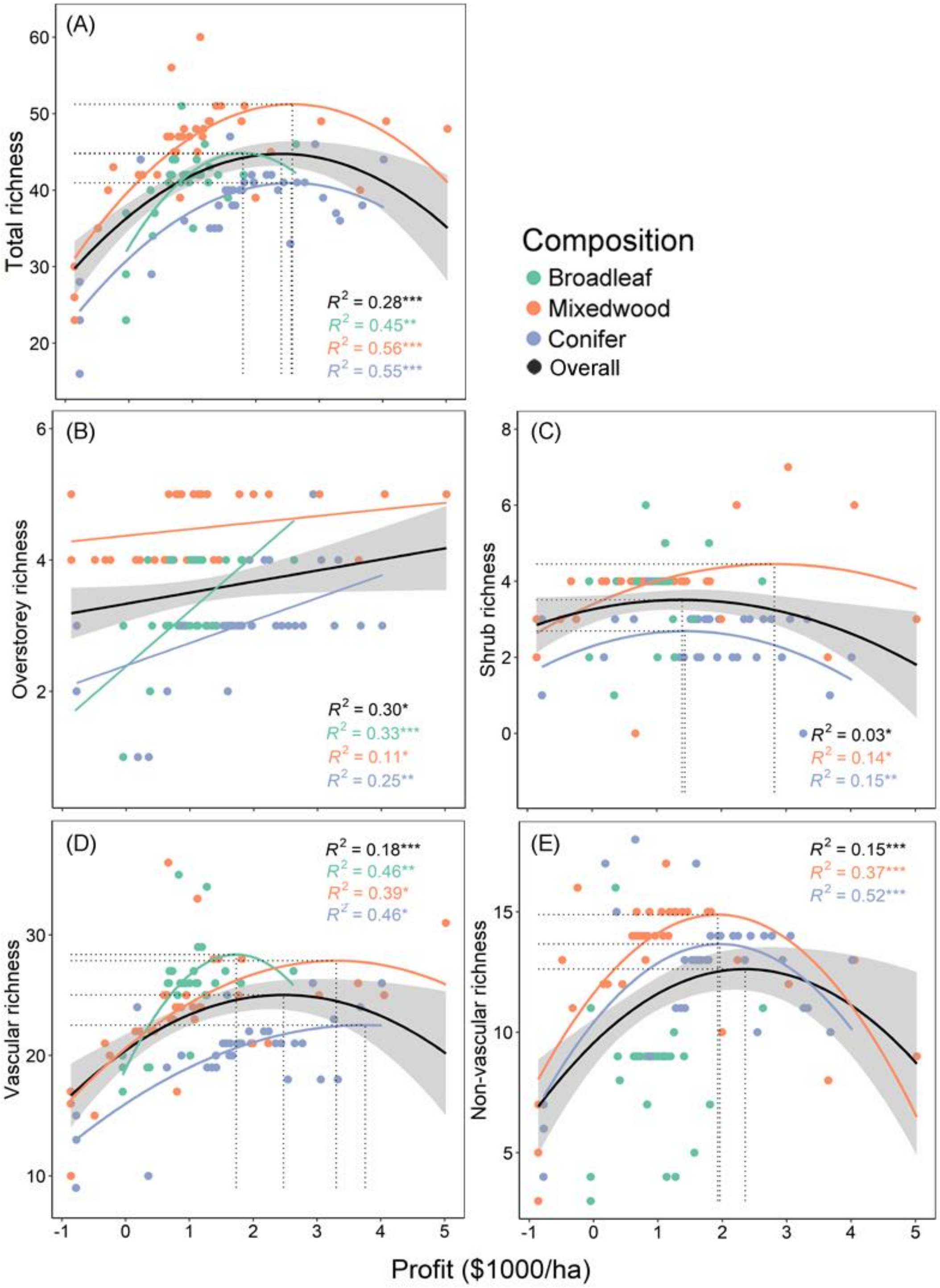

Figure 4.3. Trends in total plant richness and richness of overstorey, shrubs, and vascular and non-vascular plants with profit and in relation to overstorey composition. R^2 values are based on linear or polynomial regressions. Black lines with the shaded region are estimated mean and 95% confidence intervals. Significant differences ($\alpha = 0.05$). Significant codes (p-value): 0 _***‘, 0.001_**‘, 0.01_*‘, 0.05_.‘.

4.4.3 Path analysis results among forest management alternatives, profit, and plant diversity

Path analysis showed that rotation age positively affected profit initially, but affected it negatively after, as indicated by a positive linear term of rotation age (standardized coefficient, r = 1.50) and its negative quadratic term (r = -0.83). Rotation age positively affected total species richness initially but negatively after, as indicated by the positive linear term of rotation age (r = 2.02) and its negative quadratic term (r = -1.71). Increasing conifer composition had a direct positive effect on profit (r = 0.31) and a direct negative effect on total plant richness (r = -0.29) (Figure 4.4A). Results by individual vegetation stratum showed that rotation age also affected overstorey richness in a non-linear fashion (linear term r = 0.79, quadratic term r = -0.19), as for shrub richness (linear term r = 0.50, quadratic term r = -0.43), understorey vascular plant richness (linear term r = 1.38, quadratic term r = -0.98), and non-vascular species richness (linear term r = 1.74, quadratic term r = -1.78). Increasing conifer composition had a direct negative effect on overstorey richness (r = -0.19), shrub richness (r = -0.55), and understorey vascular plant richness (r = -0.51), but a direct positive effect on non-vascular species richness (r = 0.37) (Figures 4.4B-E).

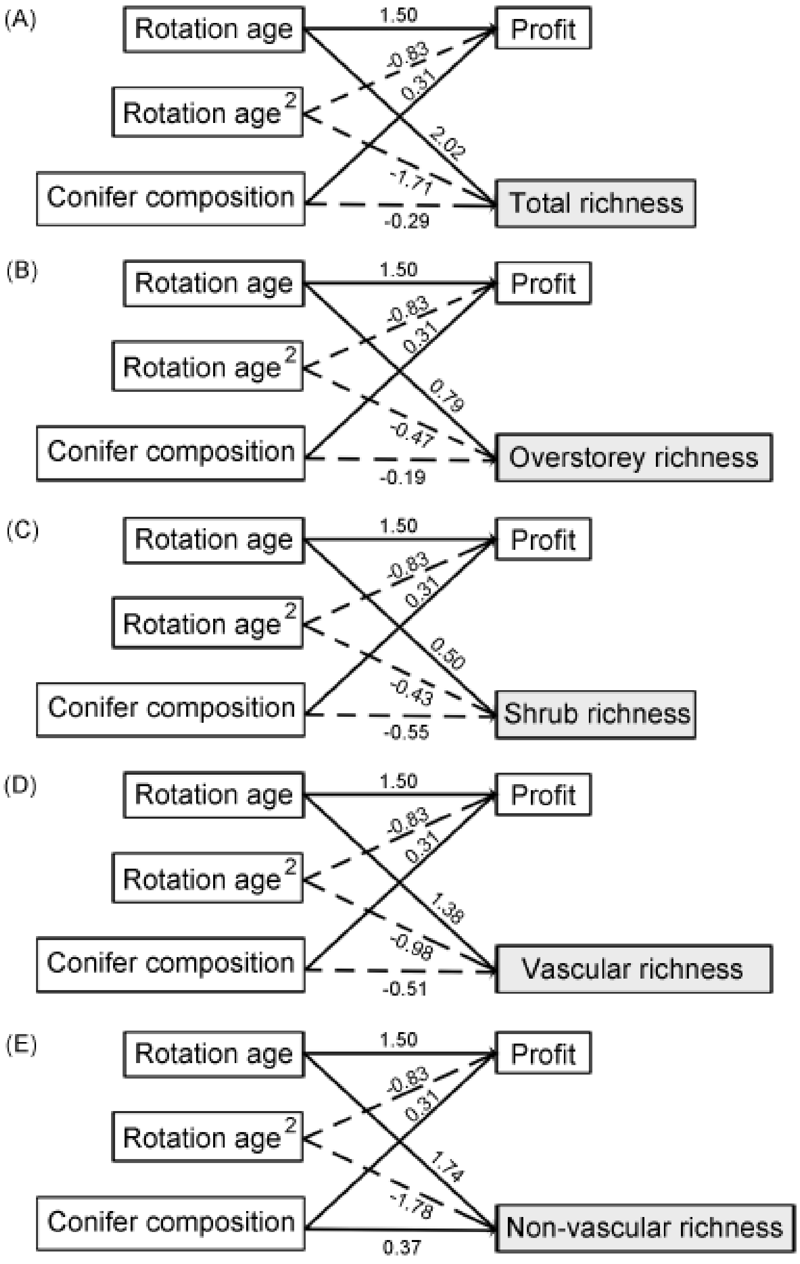

Figure 4.4. Path models showing multivariate relationships between forest management alternatives, profit and total plant richness (A), overstorey richness (B), shrub richness (C), understorey vascular plant richness (D), and non-vascular species richness (E). Solid lines represent statistically significant positive paths, while dashed lines show the significant negative path. The coefficients are standardized for each casual path.

4.5 Discussion

Our analysis is the first to evaluate the relationship between economic gains and plant diversity across vegetation strata using empirical information. We found that choice among putative forest management alternatives (managing rotation age and overstorey composition) significantly affects both economic gains (expressed as profit) and plant diversity (expressed as species richness). Economic gains differed with overstorey compositional types, with a positive linear relationship between economic gains and rotation age for mixedwood stands, but a quadratic relationship for coniferous and broadleaved stands. Rotation age-dependent trends in plant diversity also differed with overstorey compositional types and vegetation strata, with plant diversity on average higher in mixedwood than broadleaved and coniferous stands. Moreover, we found a hump-shaped relationship between economic gains and total plant diversity, and the same relationship for understorey vegetation strata. There was also a positive linear trend for economic gains and overstorey diversity.

4.5.1 Effects of forest management alternatives on economic gains and plant diversity

The trends for economic gains with rotation age are consistent with reports from previous studies, showing that maximum economic gains are achieved at intermediate rotation ages (Koskela et al. 2007, Chen et al. 2017). Longer ecological rotations may not be economically optimal, because of increased mortality rate from disturbances or interspecific competition (Luo and Chen 2011, Pyorala et al. 2014). Economic gains increase to a higher profit for coniferous stands than broadleaved stands with increasing rotation age, because mature coniferous stands fetch higher market value compared to broadleaved stands (Montigny and MacLean 2006, Mathey et al. 2009). The linear relationship for mixedwood stands with higher biomass and mix of potential products results in higher profits at later successional stages (Chen et al. 2017). Together, these results suggest that management to achieve coniferous or mixedwood stands with intermediate rotation ages (about 100 years) is recommended to achieve maximum economic gain.

Our empirical information shows that plant diversity increases and then decreases with increasing rotation age across all stand types. Higher total plant diversity at intermediate ages is likely due to the presence of gaps as a result of minor canopy disturbances and to the presence of different microsites in the form of a range of decay classes of dead wood (Beatty 1984, Bartels and Chen 2010, Kumar et al. 2017a), leading to the coexistence of both early and late successional species at intermediate stages of succession (Huston 1979, Chen and Popadiouk 2002). The decrease in plant diversity in later successional stages is attributed to reduced resource availability and increased interspecific competition for available resources (Grime 1973, Huston 1979, Rowland et al. 2005). Rotation age-dependent trends in plant diversity can be explained as increasing the time available for colonization for different plant species (Kumar et al. 2017b). These trends may also be attributed to changes in resource availability and heterogeneity following stand development in disturbance-driven boreal forests (Hart and Chen 2006, Kumar et al. 2017b).

Our results also showed that rotation age-dependent trends in a non-linear fashion in plant diversity differed among overstorey compositional types, as well as across vegetation strata. Higher plant diversity in mixedwood relative to broadleaved and coniferous stands may be attributed to the greater heterogeneity of resource availability in the understorey, which promotes the growth and development of a wider array of both vascular and non-vascular species (Huston 1979, Bartels and Chen 2010, Cavard et al. 2011). On the other hand, lower diversity in coniferous stands may be related to lower resource conditions (light and nutrient availability), and higher lignin content and carbon to nitrogen ratio of conifer litter which creates conditions favourable for bryophyte species but inhibit vascular plants (Legare et al. 2005b, Hart and Chen 2006, Bartels and Chen 2013). Our results suggest that forest management alternatives that include intermediate rotation ages and mixedwood compositional types are recommended to achieve maximum plant diversity, because mixedwood stands are generally considered to be more productive than single-species stands with better resource use and nutrient retention via niche complementarity (Tilman 1999, Loreau et al. 2001, Knoke et al. 2008, Zhang et al. 2012, Zhang et al. 2017).

4.5.2 Trade-offs and synergies between economic gains and plant diversity

The hump-shaped relationship between economic gains and total plant diversity follows a synergic pattern that is widely recognized in productivity-diversity theory, which implies that potential economic gains (mainly from the overstorey) and plant diversity both increase synergically with increasing resource availability until the limits of highest productivity (Naeem et al. 1994, Loreau et al. 2001, Zhang and Chen 2015, Liang et al. 2016). The trade-off phase may be attributed to competitive exclusion and shading effects on understorey vegetation by higher overstorey biomass (and economic gains) particularly in later successional stages (Zhang et al. 2012, Grace et al. 2016). Our results are also consistent with previous studies, which reported a non-linear relationship of biodiversity to increasing forest management intensification for economic gains (DeFries et al. 2004, Steffan-Dewenter et al. 2007, Monkkonen et al. 2014, Trivino et al. 2017). Intensive forest management aiming for single-species coniferous stands that have higher market value may result in a decrease in plant diversity and associated ecosystem services.

The differing relationships between economic gain and plant diversity among different vegetation strata also match previous research findings (Royo and Carson 2006). These differences may arise from associated changes in resource availability following intensive forest management (Gustafsson et al. 2012, Bartels et al. 2017). Maximizing economic gains facilitates overstorey richness synergically, as overstorey trees contribute substantially to economic gains, an effect known as the positive live biomass-richness relationship (Pan et al. 2012). That shrub, understorey vascular plant and non-vascular species richness show similar trends to total species richness is due to increased interspecific competition and decreased resource availability over successional time (Wardle et al. 2003, Roberts 2004). The effect leads to the trade-off relationship for decreasing plant diversity with increasing economic gains.

4.5.3 Forest management implications

Our study shows that it is difficult to achieve high levels of economic gain and maximize plant diversity simultaneously, an outcome consistent with at least one other study demonstrating that forest management aiming for all-encompassing objectives is not possible (Trivino et al. 2017). If the objective of forest management is to maximize revenues from timber harvest, then coniferous or mixedwood stands with intermediate rotation ages are recommended. If the objective is to maximize plant diversity while maintaining an economically viable management regime, mixedwood stands with intermediate ages are recommended, since mixedwood stands accumulate more merchantable volume for higher economic gains in late successional stages (Chen et al. 2017). The higher plant diversity in mixedwood stands could increase the stability of other ecological functions and optimize the provision of ecosystem services (Cardinale et al. 2012). Forest management alternatives aiming for mixedwood stands should also be promoted in boreal forests as a reflection of increasing demand for multiple value-added forest products (Mabee et al. 2011, Puddister et al. 2011, Thiffault et al. 2011).

It should be noted that our interpretation has some limitations. Firstly, natural disturbances such as wind storms, fires or pest outbreaks were not included in our simulations, even though these disturbances will have a strong influence on both economic gains and plant diversity in boreal forests (Thom and Seidl 2016). Secondly, future research will need to tackle the trade-off challenges spatially. Because economic gains are sensitive to changing costs of harvesting, processing, transportation, and production, the relationship between economic gains and plant diversity may change differently at different landscape scales and for different forest management scenarios. Finally, further research into trade-offs between economic gain and plant diversity is needed to incorporate ecological functions (ecosystem services) provided by forests, such as carbon stocks, forest site productivity, water regulation, soil fertility, and cultural services, as a recent global review suggested (Chen et al. 2016b).

4.6 Conclusion

Our findings offer new insights on how forest management options can relate to economic gains and plant diversity objectives. We found that forest management alternatives (managing rotation age and overstorey composition) affect both economic gains and plant diversity, as described in past literature. However, we also established hump-shaped trade-off relationships between profit and plant diversity following forest management alternatives (managing rotation age and overstorey composition), both in total richness and in plant richness in the understorey (shrub, understorey vascular and non-vascular species strata), and a positive linear relationship between profit and overstorey diversity. That means, maximizing potential economic gains will result in loss of plant diversity, but following appropriate forest management alternatives can ameliorate the negative trade-off, while largely maintaining and promoting synergies. We conclude that it is possible to compromise economic and plant diversity objectives by promoting mixedwood-friendly rotations (approximately 100 years) and intensive forest management practices. A systematic understanding of the relationships between economic gains and plant diversity could help forest managers and decision-makers in defining optimum forest management options that minimize ecological losses (least impact on plant diversity) while satisfying economic gains at the operational level for long-term sustainability and multi-functionality in boreal forests.

CHAPTER 5: TRADE-OFFS AND SYNERGIES BETWEEN ECONOMIC GAINS AND CARBON STOCKS ACROSS A RANGE OF MANAGEMENT ALTERNATIVES IN BOREAL FORESTS

5.1 Abstract

Boreal forests, storing approximately half of the global forest carbon (C), are key to the global C cycle and climate regulation. Forest management in boreal forests has increasingly become more intensive over time, which may have adverse impacts on the sustainability of C stocks. However, the economic gain-C stock relationship across forest management alternatives and diverse C pools remains unclear. Using empirical data, we examined the relationships between economic gains, assessed as profit, and total ecosystem C in response to the changes of rotation age and overstorey composition in boreal forests. We found that total ecosystem C increased initially, reached the maximum, and declined thereafter with increasing profit. The relationships between profit and C stocks of live biomass, deadwood, forest floor and mineral soil followed similar trends to those for total ecosystem C. However, when analyzed by overstorey composition, the relationships between profit and total deadwood C and mineral soil C were synergic (increasing together) across all studied range of profit in coniferous stands, while those were initially synergic and became trade-off (decreasing C stocks with increasing profit) in broadleaved and mixedwood stands. Our path analysis showed that both rotation age and overstorey composition simultaneously drove profit and C stocks that further led to their trade-off relationship. Our results indicated that maximum profits ($5000/ha) could lead to approximately 40% loss of total ecosystem C

while giving up 50% of profits to $2500/ha, the maximum total ecosystem C (320 Mg/ha) could be attained. Among the alternatives compared, we concluded that managing for coniferous stands with an intermediate rotation age would optimize the economic gain and C stock objectives.

5.2 Introduction

Forest ecosystem provides a multitude of ecological functions and services for economic, ecological, and social objectives to human society (Millennium Ecosystem Assessment 2005). Maximizing economic gains is an important forestry objective; however, forest management also requires to conserve or improve other ecological functions and services (Duncker et al. 2012b), including carbon (C) storage to mitigate the rising atmospheric CO_2 effects on global warming (Houghton 2007). Forest management alternatives that maximize economic gains (mainly contributed by live aboveground tree biomass) usually result in reduced *in-situ* C stocks (Schwenk et al. 2012, Kline et al. 2016). Previous studies assessing the economic gain-C stock relationships has focused on aboveground C using simulations at the landscape level (Seidl et al. 2007, Kang et al. 2016, Kline et al. 2016, Rana et al. 2017, Triviño et al. 2017). However, the empirical evidence for the relationship between economic gain and C stock of the ecosystem and the contribution of individual C pools is lacking, particularly for boreal forests where a large proportion of ecosystem C is stored in the soil (Dixon et al. 1994, Pan et al. 2011). This knowledge gap is troubling because the selection of optimum management options with limited losses of C storage capacity requires an in-depth understanding of the economic gain-C stock relationship.

Boreal forests store approximately half of the global forest C, which is the key to the global C cycle and climate regulation (Dixon et al. 1994). Management alternatives including different rotation age and overstorey composition goals determine both economic gains (Chen et al. 2017) and C stocks (Gao et al. 2017). For example, as biomass increases with rotation age, the choice of rotation age is important to the economic value of the forest products (Liski et al. 2001, Nakajima et al. 2017). Long rotations may increase the economic values of the harvest, but an excessive long rotation may result in increased tree mortality (Luo and Chen 2011) and decreased live aboveground biomass (Gao et al. 2017), reducing the economic gains. Meanwhile, rotation age could affect C stock, but with different trends among diverse C pools (Gao et al. 2017). Total live biomass C increases with age, peaks at canopy transition stage, then declines with increasing dominance of less productive late-successional species (Seedre and Chen 2010). Although deadwood C does not change notably until late successional stages, both forest floor and mineral soil C typically increase with stand development but with different magnitudes (Gao et al. 2017).

In boreal forests, overstorey species composition — controlled by natural or artificial regeneration methods at the stand initiation — influences both economic gains (Chen et al. 2017) and C stocks (Gao et al. 2017). For example, products made from coniferous wood have better market values in the Canadian forest sector than those manufactured from broadleaved wood (Chen et al. 2017). On the other hand, the higher productivity of broadleaf trees and input of soil organic C from both above- and belowground make broadleaved stands on average higher in total ecosystem C than mixedwood and coniferous stands (Laganiere et al. 2015). However, compared with broadleaved stands, coniferous stands may have higher forest floor C at intermediate stand ages, and mixedwood may have higher mineral soil C at late successional stage (Gao et al. 2017). Despite the advances made in understanding the influences of stand age and overstorey composition on C stocks (Gao et al. 2017) and economic gains (Chen et al. 2017), it remains unclear how the choices of rotation age and overstorey composition simultaneously affect economic gains and C stocks.

This study aims to examine the relationships between economic gains and total ecosystem C as well as the C stocks of total live biomass, total deadwood, forest floor, and mineral soil in response to the changes in rotation age and overstorey compositional type in the boreal forests of Canada. Specifically, we address: (i) how the relationships (trade-offs or synergies) between profit and C stocks vary with rotation age and overstorey composition across a variety of C pools; and (ii) how the choices of rotation age and overstorey composition simultaneously affect the profit and C stocks.

5.3 Methods

5.3.1 Study area and chronosequence data

Our study is located in the boreal forest region, nearly 150 km north of Thunder Bay, Ontario, Canada, between 49°44′ to 49°65′ N and 89°16′ to 90°13′ W. The characteristics of the region include warm summers and cold, snowy winters. The closest meteorological station in Cameron Falls, Ontario, Canada has recorded that the mean annual temperature is 1.9 ºC and mean annual precipitation is 824.8 mm (Environment Canada 2016). Dominant tree species in order from least to most shade tolerant, include jack pine (*Pinus banksiana* Lamb.), trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh), black spruce (*Picea mariana* (Mill) B.S.P.), white spruce (*Picea glauca* (Moench) Voss), and balsam fir (*Abies balsamea* (L.) Mill.). Due to the Wisconsinan glaciation, soil deposited in the region approximately 9,500 years ago. The prevalent natural disturbance in our study area is stand-replacing wildfire, with an average fire-return interval of approximately 100 years, in a mosaic of stand ages in the area (Senici et al. 2010). During the past 40 years, commercial logging with full-tree harvest methods has been practiced in our study area (Senici et al. 2010, Shrestha and Chen 2010).

We used a replicated chronosequence (i.e., 8, 34, 99, 147 and 210-years since stand-replacing fire), representing the stand initiation, stem exclusion, early canopy transition, late canopy transition, and gap dynamic stages of boreal forest development, respectively (Chen and Popadiouk 2002). Within each age class, we sampled three compositional types (broadleaf dominated, conifer-dominated, and mixedwood). We replicated each combination of age and overstorey type three times, resulting in a total of 45 sample stands. To ensure that the samples were interspersed to minimize spatial autocorrelation, stands were allocated several kilometers apart from each other (Legendre and Legendre 1998).

Within each of the selected stands, we randomly established 0.04 ha (11.28 m radius) circular plot, which was located > 50 m from the forest edge. For young (8-year-old) stands, we counted the tree stems by species. For older stands, we measured the diameter at breast height (DBH) for all trees. We determined entire ecosystem C by measuring all individual pools (Gao et al. 2017).

We defined overstorey type based on the percentage of broadleaf and conifer tree species using stem density for 8-year-old stands and basal area for older stands. Broadleaved and coniferous stands had > 65% broadleaved or coniferous tree species, respectively, while all other stands were classified as mixedwood stands (Hume et al. 2016). Stand age was quantified as time since last stand-replacing fire. Detailed fire records were available for stands younger than 70 years old (Senici et al. 2010). Stand age for older stands was determined through ring counts by coring three dominant/co-dominant trees of each tree species inside or near the plot.

5.3.2 Carbon stocks

As described in detail by Gao et al. (2017), the amount of C stored in the pools of total live biomass (live aboveground and live belowground), total deadwood (snags, down woody debris, and stumps), forest floor (organic soil horizons), and mineral soil was determined. In brief, total ecosystem C was the sum of all pools. Total live biomass C was the amount of C stored in all living tissues (i.e., stem, branches, twigs, foliage, and coarse and fine roots of all vegetation strata). Total deadwood C included aboveground deadwood and belowground deadwood C comprising of leaf litter, dead wood, and dead roots. The determination of forest floor C and mineral soil C has been previously described in details (Hume et al. 2016).

5.3.3 Forest management alternatives

To facilitate a trade-off analysis, a series of alternative management scenarios were developed to explore the impact of varying rotation age and overstorey composition on the economic gain-C stocks relationship. We first used regression analysis to determine empirical relationships between stand age (i.e., 8, 34, 99, 147 and 210 years) and the C stocks of total live biomass, total deadwood, forest floor, and mineral soil at varying rotation ages. Alternative sets of rotation ages were projected based on the common practices in the study region: 50-year as the ecologically and biologically acceptable rotation, 75-year as the operational rotation age under tenure (i.e., assigned to forest companies for potential harvest), 100-year as recommended by law in Ontario, and 125-year as the maximum volume accumulation with optimal ecological benefits in boreal forests (Willcocks 1997). We also extended rotation ages that varied by 5-year intervals between 75- to 100-year, rotation ages of 80, 85, 90, 95 years, because financial returns are typically highly sensitive to rotation ages. Forest Vegetation Simulator (FVS$^{\text{Ontario}}$) was used to project gross total volume for economic gains of each forest management alternative at various rotation ages (i.e., 50, 75, 80, 85, 90, 95, 100, 125-year) based on current size and calibrated values of empirical stand conditions (Woods and Robinson 2007). Existing inventory conditions of 34-year old stands were used to project volumes to rotation ages of 50, 75, 80, 85, 90, 95 years, while empirical data from 99-year stands were used to project volume to rotation ages of 100 and 125 years in FVS$^{\text{Ontario}}$. We used rotation age for the economic gains and trade-off analysis, while stand age is used to describe the plot data. We used the proportion of conifer tree species (i.e., jack pine, white spruce, black spruce and balsam fir) as a continuous variable to represent overstorey composition in each empirical case and simulated stands, expressed as a percentage of the total basal area. Intensive forest management generally resulted in a higher amount of conifer tree species in the overstorey (Chen et al. 2017).

5.3.4 Economic gains

The assumption was made that the prices of forest products and costs of silviculture, harvesting, processing, transportation, and ―all-in" delivered costs (i.e., production, shipping, distribution, and administrative expenses) were constant and co-occurred in the same year of 2016. Honer‘s equations permitted the calculation of the gross total volume of stands in each management alternative (Honer 1983). Net merchantable volume based on wood fiber recovery factor of Full-Tree to Roadside Tree-Length-to-Mill harvest method (i.e., 82.1%) was calculated by converting the gross total volume (Ride 2001). The present costs from present benefits of the six forest product assortments (i.e., lumber, softwood market pulp, hardwood market pulp, newsprint, hog fuel, and pellets) produced per hectare were substrated to calculate the economic gains, assessed as profit, for each forest management alternative within each empirical or simulated stand age (for further details, see Chen et al. (2017)).

5.3.5 Statistical analysis

We used simple or polynomial regression to examine the effect of profit on total ecosystem C stocks as well as individual C pools across overstorey compositional types. We also examined the bivariate relationships between other pairs of variables (rotation age, overstorey composition, C stocks, and profit) using simple linear or second-order polynomial regression. The most parsimonious model was chosen as having the lowest value of Akaike Information Criterion (AIC) (Burnham and Anderson 2002). The assumption of normality and homogeneity were tested by using Shapiro–Wilk‘s test and Bartlett‘s test, respectively. If normality or homogeneity was not achieved, data were bootstrapped using the estimates of regression coefficients by using the ‗*boot*‘ package in R with 4,999 iterations to generate 95% confidence intervals (CIs) (Adams et al. 1997). We used path analysis to link multivariate relationships between rotation age, overstorey composition, profit, and C stocks for the total ecosystem and individual C pools. The path analysis was applied using the *lavaan* package (Rosseel 2012). All analysis was conducted in R version 3.4.3 (R Development Core Team 2017).

5.4 Results

5.4.1 Relationship between profit and carbon stocks

Across all overstorey composition types and rotation ages, total ecosystem C was non-linearly related to profit ($P < 0.001$), with the increasing of profit, total ecosystem C reached a peak of 320 Mg/ha at a profit of \$2500/ha and decreased thereafter (Figure 5.1A). With the maximum profit at \$5000/ha, approximately 60% of the maximum total ecosystem C (190 Mg/ha) was attained (Figure 5.1A). Total ecosystem C peaked at different levels of profit among overstorey types (Figure 5.1A). Total ecosystem C peaked at 350 Mg/ha with a \$1600/ha profit for the broadleaved stands, at 330 Mg/ha with a profit of $2600/ha in mixedwood stands, and at 310 Mg/ha with a profit of $3400/ha in coniferous stands.

Similar to total forest ecosystem C, profit had hump-shaped relationships with the overall C stocks of individual C pools of total live biomass, total deadwood, forest floor, and mineral soil, which increased with increasing profits, reaching peaks, and declined afterward (Figures 5.1B-E). Averaged over all compositional types, trade-off curves showed total live biomass C, total deadwood C, forest floor C, and mineral soil C were maximized at 170 Mg/ha, 21 Mg/ha, 53 Mg/ha, and 80 Mg/ha with profits of $2600/ha, $2200/ha, $2300/ha, and $1600/ha, respectively. While the relationships between individual C pools and profit were predominantly non-linear, total deadwood C and mineral soil C increased linearly with increased profit in coniferous stands.

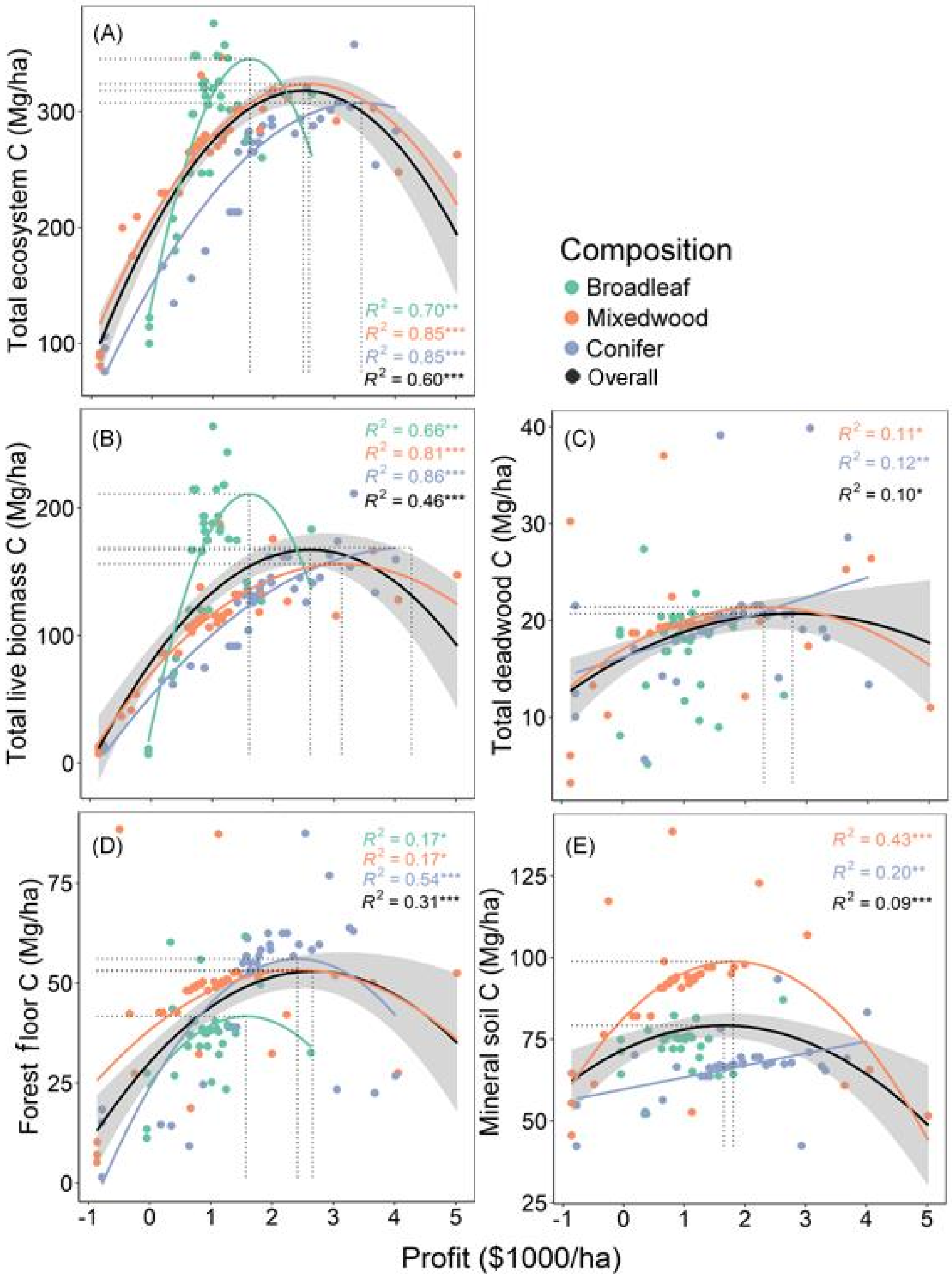

Figure 5.1. Trends in total ecosystem C, total live biomass C, total deadwood C, forest floor C and mineral soil C with profit and in relation to overstorey composition. R^2 values are based on linear or polynomial regressions. Black lines with the shaded region are estimated mean and 95% confidence intervals. Significant differences (α = 0.05). Significant codes (p-value): 0 _***‘, 0.001_**, 0.01_*‘, 0.05_.‘.

5.4.2 Effects of forest management alternatives on profit and carbon stocks

Path analysis showed that rotation age initially affected profit positively but negatively thereafter, as indicated by the quadratic standardized coefficient (r = ±0.71) (Figure 5.2). Similarly, rotation age positively affected total ecosystem C initially but negatively thereafter (r = ±0.35) (Figure 5.2A). Increasing conifer composition had a positive direct effect on profit (r = 0.27), but a negative direct effect on total ecosystem C (r = -0.35) (Figure 5.2A), primarily resulting from a negative association between total ecosystem C and conifer composition (Figure S1). The effects of rotation age and conifer composition on profit led to a quadratic effect of profit on total ecosystem C (r = ±0.39). When analyzed by overstorey compositional type, profit increased linearly with rotation age for mixedwoods but reached the maximums at approximately 125 and 175 years for coniferous and broadleaved stands, respectively (Figure 4.2).

For individual C pools, rotation age quadratically affected total live biomass C (r = ±0.37), total deadwood C (r = ±0.02), forest floor C (r = ±0.03), and mineral soil C (r = ±0.28). Increasing conifer composition had positive direct effects on total deadwood C (r = 0.02) and forest floor C (r = 0.06), but negative direct effects on total live biomass C (r = -0.36) and mineral soil C (r = -0.32) (Figures 5.2B-E). The analysis of bivariate relationships confirmed these path coefficients (Figure S1). Similarly, C stocks of all C pools were affected by profit quadratically, resulting from the effects of rotation age and conifer composition on profit and then total live biomass C, total deadwood C, forest floor C, and mineral soil C.

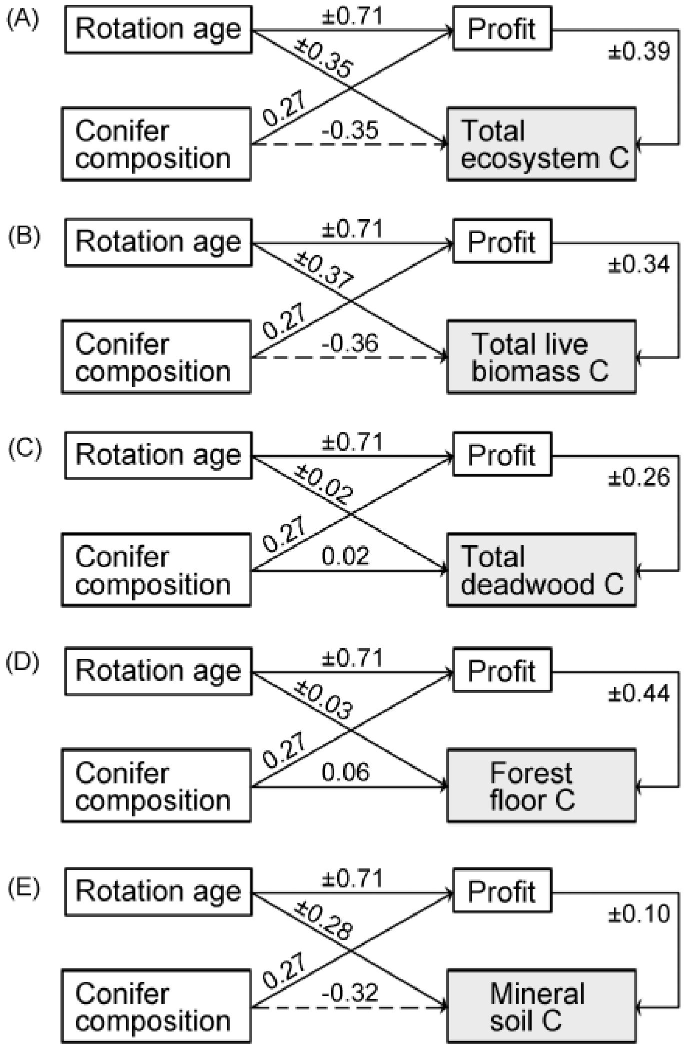

Figure 5.2. Path models showing multivariate relationships between forest management alternatives, profit and total ecosystem C, total live biomass C, total deadwood C, forest floor C and mineral soil C. Solid lines represent statistically significant positive paths, while dashed lines show the significant negative path. The coefficients are standardized for each casual path. The path coefficient marked with ‗±' indicates a quadratic relationship.

5.5 Discussion

Our analysis, to our knowledge, is the first to empirically evaluate the relationship between economic gains and C stocks in response to forest management alternatives across diverse C pools in forest ecosystems. We found a non-linear relationship between economic gains and total ecosystem C. The maximum economic gain ($5000/ha) could lead to approximately 40% loss from the maximum total ecosystem C, while giving up 50% of the economic gain to $2500/ha, the maximum total ecosystem C (320 Mg/ha) could be attained. The relationships between economic gain and individual C pools followed similar trends to those of total ecosystem C. Additionally, we found similar relationships between economic gain and C stocks for broadleaved and mixedwood stands. However, synergic relationships occurred between economic gain and total deadwood C and mineral soil C in coniferous stands.

Our empirical results showed hump-shaped relationships between economic gains and the total ecosystem C and live biomass C across forest management alternatives. These results are similar to those of previous simulation studies (Schwenk et al. 2012, Pyorala et al. 2014, Trivino et al. 2015). The initial synergic phase can be attributable to that the increasing total live biomass C simultaneously affect total ecosystem C and economic gains with the changes in stand age and overstorey compositions. However, extended rotation age can lead to reduced live biomass due to increasing longevity driven tree mortality (Luo and Chen 2011), and compositional shifts from more productive early-successional species to less productive late-successional species (Pare and Bergeron 1995, Chen and Popadiouk 2002, Taylor et al. 2014). Among overstorey types, coniferous stands had higher economic gains due to their higher market values (Chen et al. 2017), while broadleaved stands had higher total ecosystem C because of their higher productivity (Hart and Chen 2006, Augusto et al. 2015, Laganiere et al. 2015). The reduced total ecosystem C and live biomass C at high levels of economic gains are therefore attributed to their contrasting responses to extended rotation age and changes in overstorey composition.

We also found hump-shaped relationships between economic gains and the C pools of deadwood, forest floor, and mineral soil with the exceptions of deadwood C and mineral soil C in coniferous stands. At low levels of economic gains, the synergic relationships between economic gains and the C pools of deadwood, forest floor, and mineral soil are attributable to simultaneous increases in live biomass and its feedback to dead C pools with stand development following a stand-replacing disturbance in boreal forests (Seedre et al. 2011). During canopy breakup at the canopy transition stage, live biomass loss takes place sooner than increased forest floor and soil organic matter decomposition (Laganière et al. 2012). Moreover, coniferous stands with higher economic gains, however, have less forest floor and mineral soil C than broadleaved stands (Laganière et al. 2013). These divergent responses to coniferous composition and stand ageing between economic gains and the C pools of deadwood, forest floor, and mineral soil lead to their trade-offs at the high levels of economic gains.

In coniferous stands, slow decomposition rates of deadwood and aboveground litterfall could lead to the accumulation of deadwood C with stand ageing (Brassard and Chen 2008, Lang et al. 2009, Shorohova et al. 2016). As a major source of soil organic C, the slower decomposition rates of coniferous fine roots may also contribute to its higher mineral soil C (Silver and Miya 2001, Ma and Chen 2018). In the meantime, economic gains tend to increase with stand ageing in coniferous stands (Chen et al. 2017). These simultaneous increases in deadwood and mineral soil C pools, and economic gains following stand development in the coniferous stands are attributable to their synergic relationships.

Our results showed that the choices of forest management alternatives affected the economic gain-C stock relationships, and it is difficult to achieve high levels of economic gain and to maximize C stocks simultaneously. This result is consistent with at least one other study demonstrating that forest management aiming for all-encompassing objectives is not possible (Trivino et al. 2017). If the objective of forest management is to maximize economic gains, approximately 60% of total peak ecosystem C could be achieved. If the forest management objective is to maximize total ecosystem C while maintaining an economically viable management regime, approximately 50% of the maximum economic gains have to be given up. Moreover, promoting broadleaved stands could maximize total ecosystem C at an earlier rotation age with low economic gains, and mixedwood stands could provide higher total ecosystem C with intermediate economic gains, whereas managing for coniferous stands with intermediate to long rotations is optimal management option that provides both higher C stocks and economic gains among all the alternatives. Managing economic gain-C stock relationships can help avoid undesirable trade-offs while enhancing their synergies (Bennett et al. 2009, der Plas et al. 2017). These results provide broad guides for forest managers and decision-makers towards ―win-win” scenarios for C stocks and economic gains in boreal forests.

5.6 Conclusion

Based on empirical data of economic gains and diverse C pools in boreal forests across a range of forest management alternatives, our findings offer new insights into the relationships between economic gain and C stock objectives. We found hump-shaped trade-off relationships between economic gains and total ecosystem C and the C pools of total live biomass, deadwood, forest floor and mineral soil. However, when analyzed by overstorey composition, we found synergic relationships between economic gains and total deadwood C and mineral soil C across all studied ranges of economic gains in coniferous stands.

Maximizing potential economic extraction can result in trade-offs with C stocks, but it is possible to optimize economic and C objectives by promoting coniferous stands with intermediate rotation ages. Our finding can help forest policy-makers and managers to formulate policies towards —win-win” scenarios in boreal forests.

CHAPTER 6. GENERAL CONCLUSION

In summary, this dissertation provides evidence that forest management alternatives as significant drivers influencing economic gains and ecological functions (plant diversity and C stocks) across a variety of vegetation strata and C pools. We found trade-off relationships between economic gains and plant diversity/C stocks, which differed among vegetation strata and C pools. A summary of the key findings of this dissertation are as follows:

1. Through the global review of economic and ecological trade-off analysis, we summarized the major economic and ecological trade-off methods (monetary valuation, biophysical models, optimization programming, production possibility frontier and multi-objective optimization) that are commonly employed in making forest management decisions. We also found that economic and ecological trade-offs are poorly understood for boreal forests following forest management alternatives. Therefore, we focused our further economic analysis on understanding the trade-offs between economic gains and ecological functions following forest management alternatives in the boreal forests.
2. In the economic analysis of forest management alternatives study, we provided evidence of how four forest management alternatives (silvicultural intensity, forest composition, rotation age, and harvest method) affect economic gains in boreal forests. We found that all four forest management alternatives listed above significantly affected economic gains. The most optimum combination of forest management alternatives, from an economic point of view, were found to have low silvicultural intensity (conifer – conifer), with a rotation age of 100 years, and using Full-Tree to Roadside Tree-Length-to-Mill harvesting method.

3. In the economic gain-plant diversity relationship study, we found hump-shaped trade-off relationships between economic gains and plant diversity following forest management alternatives (managing rotation age and overstorey composition), both in total species diversity and in the understorey diversity (shrub, understorey vascular and non-vascular plant strata), but a positive linear relationship between economic gains and overstorey diversity. Therefore, promoting mixedwood-friendly rotations at approximately 100 years is the optimal management practices to compromise between economic gains and plant diversity objectives.
4. In the economic gain-C stock relationship study, we found hump-shaped trade-off relationships between economic gains and total ecosystem C. The relationships between profit and C stocks of diverse C pools (total live biomass, total deadwood, forest floor and mineral soil) followed similar trends to total ecosystem C. However, when analyzed by overstorey composition, we found synergic (increasing together) relationships between economic gains and total deadwood C and mineral soil C across all studied ranges of economic gains in coniferous stands. Whereas for mixedwood and broadleaved stands, the relationship was initially synergic (increasing C stocks with increasing economic gains) and became trade-off (decreasing C stocks with increasing economic gains) in broadleaf and mixedwood stands. The results suggested that coniferous stands with intermediate rotation ages (approximately100 years) are the optimum compromise to achieve both economic gains and C stock objectives in the boreal forests.

The findings of this dissertation extended our understanding of trade-offs or synergies of economic gains and ecological functions responding to forest management alternatives in the boreal forests. Practically, this thesis is part of a larger picture of forest management decisions and guideline to facilitate further economic-ecological trade-off studies in the boreal forests. The outcomes will contribute to developing and implementing strategies for sustainable forest management that can simultaneously produce economic gains and ecological functions in the boreal forests.

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APPENDIX I. SUPPLEMENTAL INFORMATION FOR CHAPTER 3

Table S1. Gross total volume (GTV), net merchantable volume (NMV) and biomass of stands using the three harvesting methods and rotation ages for the three compositions in the boreal forests of Ontario, Canada.

			FT-TL		FT-SW		CTL
Stand age (years)	Overstory[a]	GTV (m^3/ha)[b]	NMV[b] (m^3/ha)	Biomass[b] (GMT/ha)	NMV[b] (m^3/ha)	Biomass[b] (GMT/ha)	NMV[b] (m^3/ha)
34	B	156.75 (3.25)	130.99 (4.5)	1.49 (0.22)	130.99 (4.5)	1.49 (0.22)	130.99 (4.5)
34	C	117.18 (6.58)	95.12 (5.71)	5.83 (0.25)	89.23 (5.36)	5.83 (0.25)	101.25 (6.08)
34	M	84.96 (3.38)	72.26 (2.94)	1.9 (0.2)	70.25 (2.82)	1.9 (0.2)	74.35 (3.06)
50	B	258.27 (4.08)	218.72 (7.87)	6.36 (0)	218.72 (7.87)	6.36 (0)	218.72 (7.87)
50	C	228.5 (2.59)	187.6 (2.12)	7.92 (0)	175.94 (1.99)	7.92 (0)	199.71 (2.26)
50	M	209.33 (9.03)	180.7 (8.04)	4.92 (0.33)	177.33 (8.08)	4.92 (0.33)	184.6 (8.0)
75	B	290.7 (2.0)	242.53 (4.74)	0.99 (0.28)	242.53 (4.74)	0.99 (0.28)	242.53 (4.74)
75	C	272.97 (3.74)	229.67 (4.04)	4.9 (0.01)	210.18 (2.88)	4.9 (0.01)	238.57 (3.27)
75	M	330.8 (13.0)	286.13 (11.59)	4.47 (0.25)	280.66 (11.65)	4.47 (0.25)	291.8 (11.54)
80	B	313.5 (5.71)	276.52 (4.54)	4.7 (0.42)	275.54 (4.14)	4.7 (0.42)	260.84 (2.15)
80	C	289.83 (3.99)	237.95 (3.27)	4.7 (0.01)	223.17 (3.07)	4.7 (0.01)	253.31 (3.48)
80	M	350.5 (13.1)	303.75 (11.42)	4.89 (0.36)	297.93 (11.49)	4.89 (0.36)	309.79 (11.37)
85	B	309.67 (6.91)	274.36 (6.12)	4.41 (0.41)	274.36 (6.12)	4.41 (0.41)	274.36 (6.12)
85	C	305 (6.98)	250.67 (5.73)	7.53 (1.15)	5.1 (5.37)	7.53 (1.15)	266.86 (6.10)
85	M	370.56 (12.78)	321.10 (11.13)	4.87 (0.34)	314.91 (11.19)	4.87 (0.34)	327.5 (11.08)
90	B	317.97 (9.55)	280.17 (7.81)	4.17 (0.44)	278.96 (7.3)	4.17 (0.44)	260.66 (0.53)
90	C	312.67 (7.49)	264.09 (6.15)	9.78 (1.29)	247.68 (5.77)	9.78 (1.29)	281.13 (6.55)
90	M	376.2 (1.61)	344.02 (9.22)	3.87 (0.29)	336.91 (9.08)	3.87 (0.29)	351.41 (9.39)
95	B	321.37 (10.30)	284.73 (9.12)	3.47 (0.22)	284.73 (9.12)	3.47 (0.22)	284.73 (9.12)
95	C	343.33 (8.85)	281.88 (7.27)	11.33 (0.83)	264.37 (6.81)	11.33 (0.83)	300.07 (7.74)
95	M	420.23 (9.14)	365.14 (9.29)	8.0 (1.68)	356.83 (9.32)	8.0 (1.68)	373.78 (9.27)
100	B	383.47 (26.97)	335 (23.87)	3.56 (0.96)	334.7 (23.98)	3.56 (0.96)	330.18 (25.74)
100	C	329.98 (14.4)	305.95 (9.15)	19.94 (0.68)	271.11 (8.58)	19.94 (0.68)	307.73 (9.75)
100	M	296.9 (9.65)	198 (20.57)	32.45 (10.07)	192.75 (20.55)	32.45 (10.07)	203.36 (20.60)
125	B	314.57 (7.55)	278.7 (6.69)	2.55 (0.71)	278.7 (6.69)	2.55 (0.71)	278.71 (6.69)
125	C	313.33 (5.67)	257.24 (4.65)	10.38 (0.03)	241.27 (4.36)	10.38 (0.03)	273.85 (4.95)
125	M	386.63 (18.92)	303.57 (26.15)	14.8 (0.55)	295.98 (26.0)	14.8 (0.55)	311.45 (26.3)
147	B	358.7 (18.51)	84.67 (21.03)	16.10 (5.65)	284.68 (21.03)	16.10 (5.65)	284.68 (21.03)
147	C	284.88 (23.07)	240.40 (17.3)	23.5 (2.95)	225.48 (16.22)	23.5 (2.95)	255.93 (18.4)

147	M	260.32 (12.50)	190.35 (18.66)	36.31 (6.44)	186.23 (18.51)	36.31 (6.44)	194.63 (18.8)
210	B	279.63 (12.92)	236.42 (13.40)	11.86 (1.88)	233.96 (13.73)	11.86 (1.88)	238.66 (13.1)
210	C	289.16 (27.33)	218.82 (18.1)	31.94 (5.32)	205.8 (16.72)	31.94 (5.32)	232.36 (19.54)
210	M	342.26 (13.87)	203.35 (17.03)	82.3 (6.9)	193.03 (16.51)	82.3 (6.9)	213.03 (17.6)

All overstory-age combination was replicated (3 stands)

[a] Overstory types: B – broadleaf, C – conifer, and M – mixedwood.

[b] Values are means with 1 stand error in parentheses.

Table S2. Profits of stands sampled or projected using the harvesting methods and rotation ages for the three compositions in the boreal forests of Ontario, Canada.

			FT-TL		**FT-SW**		**CTL**	
Stand age (years)	Overstory[a]	Silvicultural Intensity	Profits ($/ha)[b]		Profits ($/ha)[b]		Profits ($/ha)[b]	
34	B	B-B	375.07 (14.99)	375.07 (8.65)	375.07 (14.99)	375.07 (8.65)	322.4 (22.05)	322.4 (12.73)
		M-B	375.07 (14.99)		375.07 (14.99)		322.4 (22.05)	
		C-B	375.07 (14.99)		375.07 (14.99)		322.4 (22.05)	
34	C	B-C	55.43 (110.4)	395.4 (118.67)	-309.753 (73.18)	30.22 (108.65)	-553.02 (58.46)	-213.05 (105.63)
		M-C	345.0 (110.4)		-20.1833 (73.18)		-263.46 (58.46)	
		C-C	785.77 (110.4)		420.5867 (73.18)		177.31 (58.46)	
34	M	B-M	-610.9 (57.68)	-353.20 (70.24)	-735.603 (41.89)	-477.9 (66.4)	55.43 (110.42)	-556.09 (63.67)
		M-M	-181.72 (57.68)		-306.423 (41.89)		345 (110.42)	
		C-M	-266.97 (57.68)		-391.673 (41.89)		785.77 (110.42)	
50	B	B-B	759.92 (75.78)	759.92 (43.75)	795.92 (75.78)	795.92 (43.75)	570.35 (38.54)	570.35 (22.25)
		M-B	759.92 (75.78)		795.92 (75.78)		570.35 (38.54)	
		C-B	759.92 (75.78)		795.92 (75.78)		570.35 (38.54)	
50	C	B-C	1010.86 (33.5)	1350.83 (101.94)	288.88 (19.35)	628.85 (100.72)	-0.65 (21.93)	339.32 (100.89)
		M-C	1300.43 (33.5)		578.45 (19.35)		288.92 (21.93)	
		C-C	1741.20 (33.5)		1019.22 (19.35)		729.69 (21.93)	
50	M	B-M	15.47 (72.56)	273.17 (74.69)	-206.23 (66.54)	51.47 (72.8)	-427.63 (43.0)	-169.93 (66.63)
		M-M	444.65 (72.56)		222.95 (66.54)		1.55 (43.0)	
		C-M	359.4 (72.56)		137.7 (66.54)		-83.7 (43.0)	
75	B	B-B	672.79 (4.38)	672.79 (2.53)	572.79 (4.38)	672.79 (2.53)	637.62 (23.2)	637.62 (13.40)
		M-B	672.79 (4.38)		572.79 (4.38)		637.62 (23.2)	
		C-B	672.79 (4.38)		572.79 (4.38)		637.62 (23.2)	
75	C	B-C	1233.48 (65.04)	1573.45 (106.9)	320.34 (29.26)	660.31 (101.5)	217.13 (31.75)	557.10 (101.76)
		M-C	1523.05 (65.04)		609.91 (29.26)		506.70 (31.75)	
		C-C	1963.82 (65.04)		1050.68 (29.26)		947.47 (31.75)	
75	M	B-M	479.77 (89.56)	737.47 (80.61)	141.26 (79.0)	398.97 (76.84)	-35 (58.78)	222.7 (70.54)
		M-M	908.95 (89.56)		570.44 (79.0)		394.18 (58.78)	
		C-M	823.7 (89.56)		485.19 (79.0)		308.93 (58.78)	
80	B	B-B	1082.64	1082.64 (76.1)	524.54 (36.0)	524.54 (20.79)	689.37 (10.53)	689.37 (6.08)

			(131.81)					
		M-B	1082.64 (131.81)		524.54 (36.0)		689.37 (10.53)	
		C-B	1082.64 (131.81)		524.54 (36.0)		689.37 (10.53)	
80	C	B-C	1298.35 (52.43)	1638.32 (104.57)	382.57 (30.6)	722.54 (101.64)	299.73 (33.82)	639.7 (101.98)
		M-C	1587.92 (52.43)		672.14 (30.6)		589.30 (33.82)	
		C-C	2028.69 (52.43)		1112.91 (30.6)		1030.07 (33.82)	
80	M	B-M	587.61 (96.21)	845.31 (83.13)	227.2 (87.1)	484.9 (79.7)	32.68 (58.77)	
		M-M	1016.79 (96.21)		656.38 (87.1)		461.86 (58.77)	
		C-M	931.54 (96.21)		571.12 (87.1)		376.60 (58.77)	
85	B	B-B	962.39 (67.53)	962.39 (39.0)	573.13 (8.13)	573.13 (4.70)	727.60 (29.95)	727.60 (17.29)
		M-B	962.39 (67.53)		573.13 (8.13)		727.60 (29.95)	
		C-B	962.39 (67.53)		573.13 (8.13)		727.60 (29.95)	
85	C	B-C	1564.68 (187.99)	1904.65 (147.64)	599.92 (152.27)	939.89 (133.22)	375.65 (59.22)	715.61 (105.77)
		M-C	1854.25 (187.99)		889.49 (152.27)		665.21 (59.22)	
		C-C	2295.02 (187.99)		1330.26 (152.27)		1105.99 (59.22)	
85	M	B-M	671.85 (96.0)	929.56 (83.0)	289.0 (84.85)	546.7 (78.89)	99.99 (58.27)	357.70 (70.40)
		M-M	1101.03 (96.0)		718.18 (84.85)		529.17 (58.27)	
		C-M	1015.78 (96.0)		632.93 (84.85)		443.92 (58.27)	
90	B	B-B	910.89 (38.17)	910.89 (22.04)	542.8 (28.5)	542.8 (16.5)	688.87 (2.59)	688.87 (1.49)
		M-B	910.89 (38.17)		542.8 (28.5)		688.87 (2.59)	
		C-B	910.89 (38.17)		542.8 (28.5)		688.87 (2.59)	
90	C	B-C	1806.73 (208.77)	2146.7 (156.67)	790.37 (169.94)	1130.34 (140.16)	455.64 (63.58)	795.6 (106.61)
		M-C	2096.30 (208.77)		1079.94 (169.94)		745.20 (63.58)	
		C-C	2537.07 (208.77)		1520.71 (169.94)		1185.98 (63.58)	
90	M	B-M	777.61 (73.76）	1035.31 (75.08)	337.10 (35.2)	594.8 (65.1)	211.82 (67.70)	469.52 (73.16)
		M-M	1206.79 (73.76)		766.28 (35.2)		641 (67.70)	
		C-M	1121.54 (73.76)		681.0 (75.2)		555.75 (67.70)	
95	B	B-B	941.68 (64.58)	941.68 (37.28)	941.68 (64.6)	941.68 (37.3)	756.90 (44.67)	756.90 (25.79)

		M-B	941.68 (64.58)		941.68 (64.6)		756.90 (44.67)	
		C-B	941.68 (64.58)		941.68 (64.6)		756.90 (44.67)	
95	C	B-C	2051.45 (190.85)	2391.42 (148.86)	966.62 (142.5)	1306.59 (129.57)	561.75 (75.1)	901.72 (109.08)
		M-C	2341.01 (190.85)		1256.19 (142.5)		851.32 (75.1)	
		C-C	2781.79 (190.85)		1696.96 (142.5)		1292.09 (75.1)	
95	M	B-M	1178.43 (138.45)	1436.13 (101.06)	663.69 (149.53)	921.39 (106.19)	332.06 (44.03)	589.77 (66.86)
		M-M	1607.61 (138.45)		1092.87 (149.53)		761.24 (44.03)	
		C-M	1522.36 (138.45)		1007.62 (149.53)		675.99 (44.03)	
100	B	B-B	1118.41 (117.18)	1118.41 (67.66)	1074.37 (153.11)	1074.37 (88.4)	885.32 (125.99)	885.32 (72.74)
		M-B	1118.41 (117.18)		1074.37 (153.11)		885.32 (125.99)	
		C-B	1118.41 (117.18)		1074.37 (153.11)		885.32 (125.99)	
100	C	B-C	2574.59 (170.18)	2914.56 (140.26)	1462.1 (115.27)	1802.07 (120.2)	604.63 (94.60)	944.60 (114.02)
		M-C	2864.16 (170.18)		1751.67 (115.27)		894.20 (94.60)	
		C-C	3304.93 (170.18)		2192.44 (115.27)		1334.97 (94.60)	
100	M	B-M	1692.44 (886.0)	1950.15 (503.8)	1370.15 (860.8)	1627.85 (500.84)	-297.4 (103.30)	-39.7 (85.91)
		M-M	2121.62 (886.0)		1799.33 (860.8)		131.77 (103.30)	
		C-M	2036.37 (886.0)		1714.08 (860.8)		46.52 (103.30)	
125	B	B-B	830.16 (97.86)	830.16 (56.5)	830.16 (97.86)	830.16 (56.5)	739.87 (32.74)	739.87 (18.90)
		M-B	830.16 (97.86)		830.16 (97.86)		739.87 (32.74)	
		C-B	830.16 (97.86)		830.16 (97.86)		739.87 (32.74)	
125	C	B-C	1776.49 (76.21)	2116.46 (109.34)	786.46 (45.2)	1126.43 (103.44)	55.43 (110.42)	745.79 (103.87)
		M-C	2066.06 (76.21)		1076.03 (45.2)		345 (110.42)	
		C-C	2506.83 (76.21)		1516.8 (45.2)		785.77 (110.42)	

125	M	B-M	1293.84 (112.49)	1551.54 (86.68)	823.87 (90.86)	1081.58 (81.09)	121.52 (143.73)	379.22 (103.49)
		M-M	1723.02 (112.49)		1253.05 (90.86)		550.7 (143.73)	
		C-M	1637.77 (112.49)		1167.8 (90.86)		465.45 (143.73)	
147	B	B-B	1613.23 (418.14)	1613.23 (241.41)	1613.23 (418.1)	1613.23 (241.4)	756.74 (102.96)	756.74 (59.45)
		M-B	1613.23 (418.14)		1613.23 (418.1)		756.74 (102.96)	
		C-B	1613.23 (418.14)		1613.23 (418.1)		756.74 (102.96)	
147	C	B-C	2320.71 (439.74)	2660.68 (272.9)	1395.48 (353.2)	1735.45 (227.2)	314.38 (178.76)	654.35 (143.77)
		M-C	2610.28 (439.74)		1685.1 (353.2)		603.95 (178.76)	
		C-C	3051.05 (439.74)		2125.8 (353.2)		1044.72 (178.76)	
147	M	B-M	1766.64 (531.64)	2024.34 (313.11)	1511.36 (522.5)	1769.1 (307.9)	-373.56 (108.46)	-115.85 (88.0)
		M-M	2195.81 (531.64)		1940.5 (522.5)		55.62 (108.46)	
		C-M	2110.57 (531.64)		1855.3 (522.5)		-29.62 (108.46)	
210	B	B-B	1501.69 (161.16)	1501.69 (93.05)	1348.56 (128.0)	1348.56 (73.91)	745.28 (41.97)	745.28 (24.23)
		M-B	1501.69 (161.16)		1348.56 (128.0)		745.28 (41.97)	
		C-B	1501.69 (161.16)		1348.56 (128.0)		745.28 (41.97)	
210	C	B-C	2516.03 (812.64)	2856 (479.74)	1708.98 (666.7)	2048.95 (397.7)	156.99 (209.40)	496.96 (156.96)
		M-C	2805.6 (812.64)		1998.55 (666.7)		446.56 (209.40)	
		C-C	3246.37 (812.64)		2439.3 (666.7)		887.33 (209.40)	
210	M	B-M	3296.35 (713.9)	3554.05 (416.78)	2719.26 (799.5)	2976.96 (465.7)	-74.34 (140.2)	183.37 (101.87)
		M-M	3725.53 (713.9)		3148.44 (799.5)		354.84 (140.2)	

C-M	3640.28 (713.9)	3063.19 (799.5)	269.59 (140.2)

All overstory-age combination was replicated (3 stands)

[a] Overstory types: B – broadleaf, C – conifer, and M – mixedwood.

[b] Values are means with 1 stand error in parentheses.

APPENDIX II. SUPPLEMENTAL INFORMATION FOR CHAPTER 5

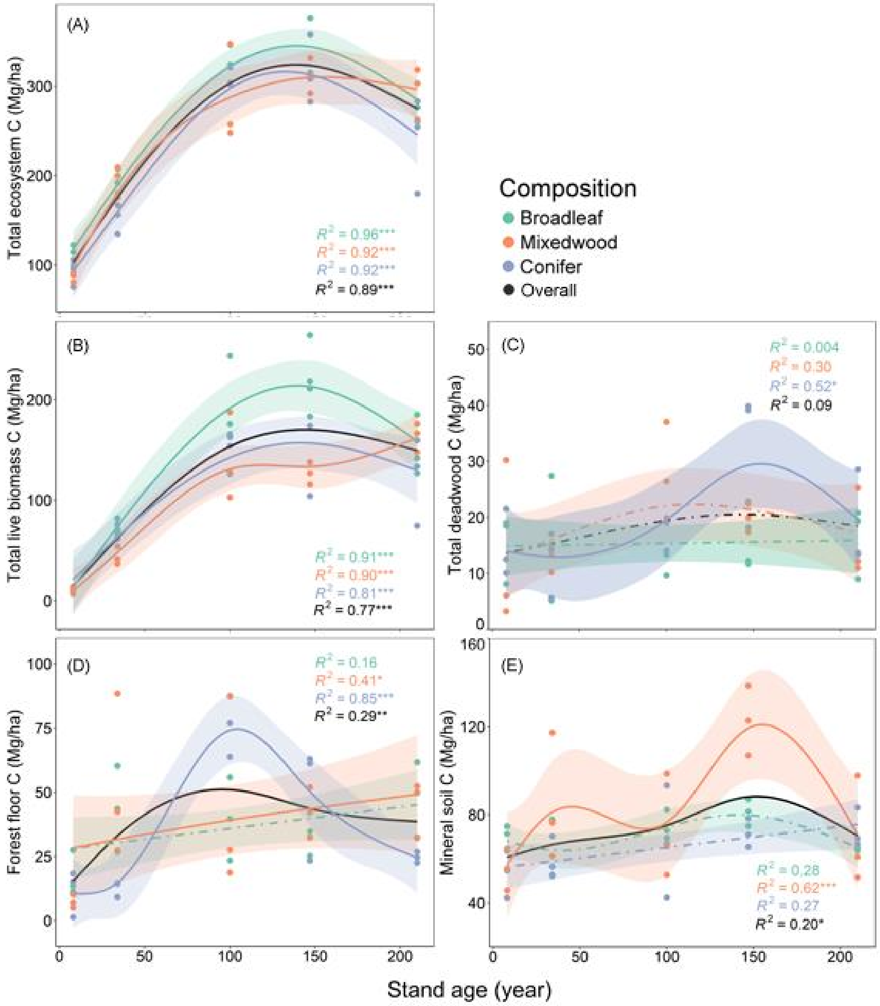

Figure S1. Trends in total ecosystem carbon (C), total live biomass C, total deadwood C, forest floor C and mineral soil C with rotation age and overstorey composition. The lines indicate smooth functions of the best model fit for the long-term trends using general additive models (GAM). Solid lines represent statistically significant trends while dashed lines show the insignificant trends. Shaded regions are the approximate 95% confidence intervals. R^2 values indicate the model fit. Significant differences ($\alpha = 0.05$). Significant codes (p-value): 0 _***‘; 0.001_**‘, 0.01_*‘.