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Economic and Ecological Trade-Off Analysis of Forest Ecosystems: Options for Boreal Forests

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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.

Keywords: boreal forest, ecological functions, economic gains, ecosystem services, multi-objective optimization, trade-offs

1. 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. Approach

2.1 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.

2.2 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 key words, 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.

3. Current state of trade-off studies

The spatial distribution of the studies, using economic and ecological comparison methods, encompassed an extensive global reach (Fig. 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%) (Fig. 2).

4. 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) (Fig. 3).

4.1 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.

4.2 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. 2012). 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. 2012; 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. 2012; 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. 2012; 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.

4.3 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 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.

4.4 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 twodimensional efficiency frontier, whereas actual forest management challenges often include multiple conflicting objectives (Calkin et al. 2002).

4.5 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), are 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 (Díaz-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.

5 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 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 may 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 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).

6 The need for trade-off studies in boreal forests

6.1 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).

6.2 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.

6.3 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) (Fig. 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).

6.4 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 1). Future trade-off analysis shall simultaneously consider additional ecological objectives.

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).

6.5 Inclusion of social aspects

It is also important to develop forest management policies through exploring multi-objectives modelling 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.

7. 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.

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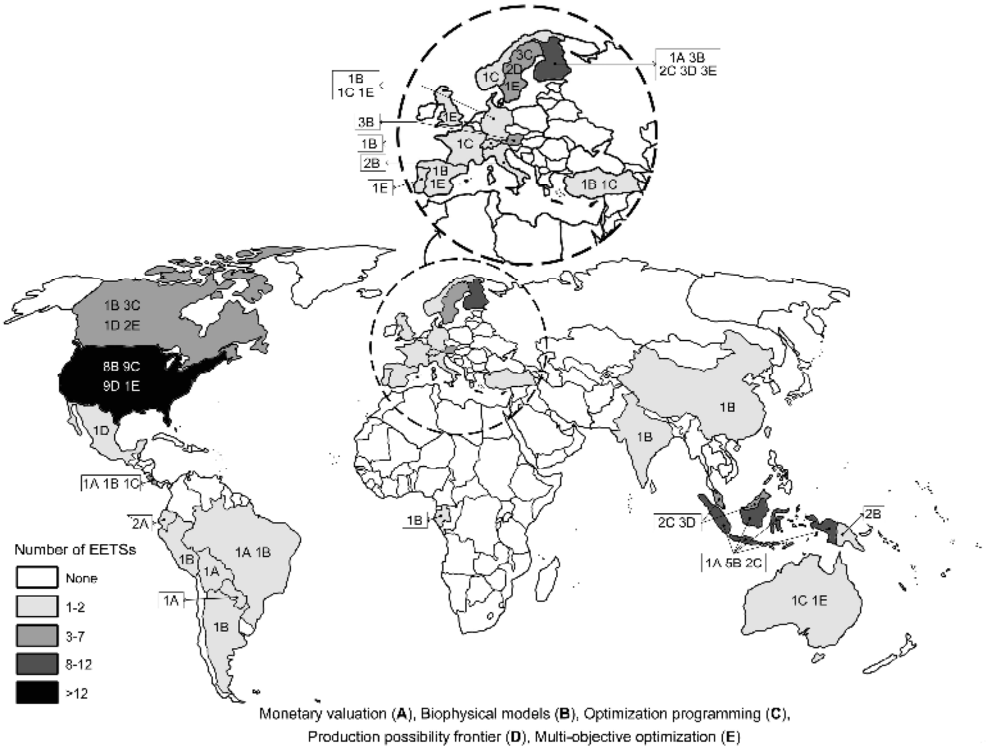

Fig. 1. Geographical distribution of economic and ecological trade-off studies (EETSs).
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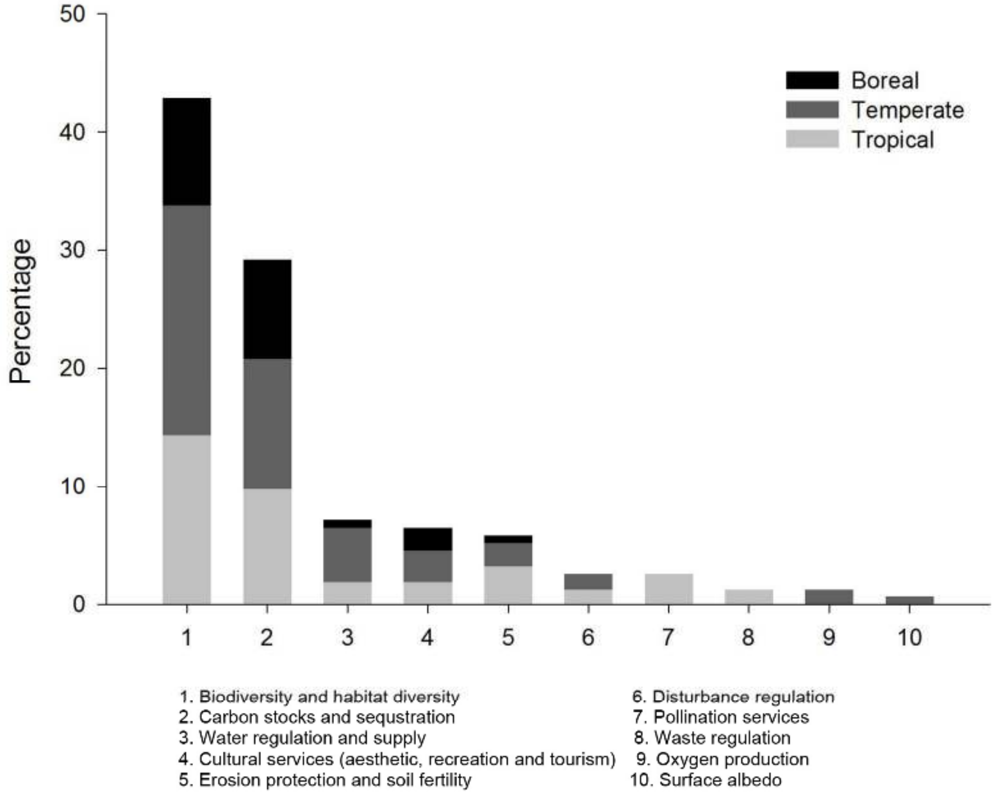

Fig. 2. Percentage of ecological functions and ecosystem services involved in the economic and ecological trade-off studies.
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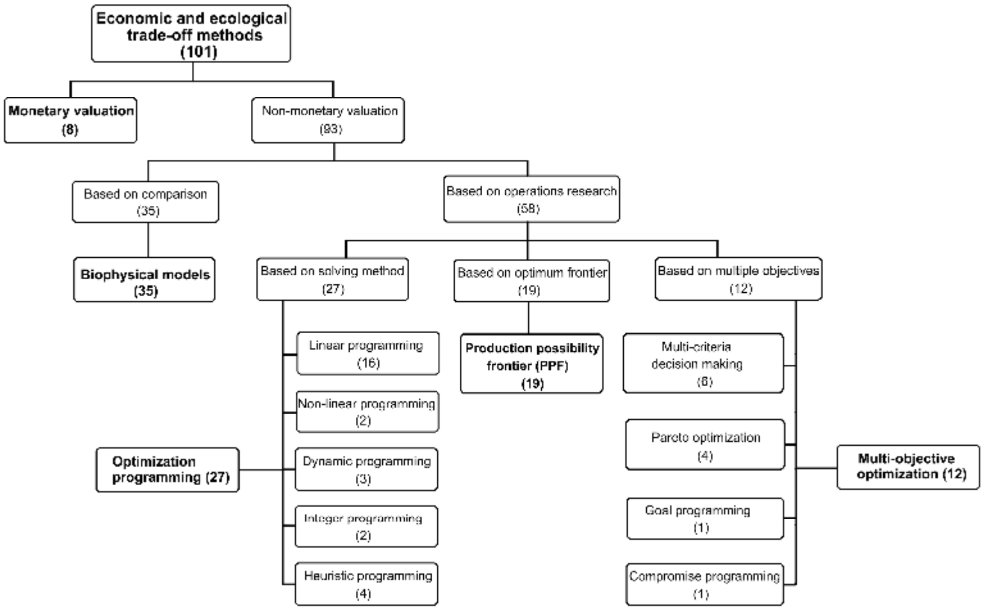

Fig. 3. Classification of primary economic and ecological trade-off methods.
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Table 1. Comparison of economic and ecological trade-off studies in boreal forests.

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)

Table 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	Conversion of solar energy into biomass	Plant growth

	production	through photosynthesis	
	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 boreal species	Plant diversity, refugium for resident and migratory species, nurseries for spawning
	Maintenance of genepool	Maintenance of genetic diversity in boreal forest	Endemic species, threatened species (e.g., caribou)
	Hydrological cycle	Movement and storage of water	Evapotransporation, 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	Erosion control of soil, and maintenance of soil fertility in boreal forests	Prevention of soil loss by wind and runoff

	soil fertility		
	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 human arts and heritage	Inspirational value, books, paintings in Indigenous communities
	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).