Ambio 2017, 46:743–755
DOI 10.1007/s13280-017-0919-5

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

CrossMark

REVIEW

Impacts of forestry on boreal forests: An ecosystem services perspective

Tähti Pohjanmies, María Triviño, Eric Le Tortorec, Adriano Mazziotta, Tord Snäll, Mikko Mönkkönen

Received: 29 April 2016 / Revised: 21 August 2016 / Accepted: 7 April 2017 / Published online: 22 April 2017

Abstract Forests are widely recognized as major providers of ecosystem services, including timber, other forest products, recreation, regulation of water, soil and air quality, and climate change mitigation. Extensive tracts of boreal forests are actively managed for timber production, but actions aimed at increasing timber yields also affect other forest functions and services. Here, we present an overview of the environmental impacts of forest management from the perspective of ecosystem services. We show how prevailing forestry practices may have substantial but diverse effects on the various ecosystem services provided by boreal forests. Several aspects of these processes remain poorly known and warrant a greater role in future studies, including the role of community structure. Conflicts among different interests related to boreal forests are most likely to occur, but the concept of ecosystem services may provide a useful framework for identifying and resolving these conflicts.

Keywords Conflict · Forest management · Sustainability · Timber production · Trade-off

INTRODUCTION

Boreal forests account for approximately one-third of the world's forest cover (UNEP et al. 2009). These forests are a major source of timber products, but also provide a range of other goods and services that are essential to human well-being (Vanhanen et al. 2012; Brandt et al. 2013; Gauthier et al. 2015). In general, the multifunctional role of forests is widely recognized within science (Harrison et al. 2010) and policy (e.g., the EU Forestry Strategy[1]). Boreal forests have a crucial role in global climate regulation and climate change mitigation (Pan et al. 2011). They also harbor unique biodiversity, and the biome includes some of the world's largest areas of intact primary forest (UNEP et al. 2009). Therefore, the development of boreal forests in the coming decades is of great importance for both humans and global biodiversity.

Unlike tropical and temperate forests, boreal forests as a whole have remained relatively stable in area in recent decades (UNEP et al. 2009; FAO 2015). In several boreal countries, forest conversion is discouraged by regulatory measures, and overall, the region is characterized by a net gain in growing forest stock (FAO 2015). However, extensive tracts of boreal forests are actively managed and harvested for timber production, with changes to the structure of the forests and impacts on wildlife and ecosystem functioning (Bradshaw et al. 2009; Kuuluvainen et al. 2012; Venier et al. 2014). Throughout the boreal region, even though intact forests are concentrated in the northernmost or otherwise inaccessible regions, still they are not extensively protected (Potapov et al. 2008). Moreover, there is ongoing pressure to harvest more forest biomass, for example, to increase the use of renewable energy according to set targets. The suggested ways of intensifying forest biomass production to achieve this (e.g., fertilization, tree species choice, and whole-tree harvesting) may further aggravate forestry's impacts on ecosystems (Laudon et al. 2011).

The concept of ecosystem services (Millennium Ecosystem Assessment 2005) provides a framework for describing the multifunctional role of ecosystems, for

Electronic supplementary material The online version of this article (doi:10.1007/s13280-017-0919-5) contains supplementary material, which is available to authorized users.

[1] http://ec.europa.eu/agriculture/forest/strategy/index_en.htm.

assessing the impacts of ecosystem management comprehensively, and for planning management strategies that balance conflicting interests. Ecosystem services are defined as the benefits human populations obtain directly or indirectly from the ecosystem structures and functions (Costanza et al. 1997; Millennium Ecosystem Assessment 2005). Besides timber, boreal production forests are actively used as a source of collectable goods and recreation, and provide a range of other ecosystem services, including climate regulation, water purification, maintenance of soil productivity, and air-quality regulation (Vanhanen et al. 2012; Brandt et al. 2013). The widespread acknowledgement of forests as major providers of ecosystem services is illustrated by the common use of forest cover as an indicator of several ecosystem services (e.g., Maes et al. 2016) or assignment of high values of service supply to forests compared with other land cover types (e.g., Vihervaara et al. 2010). However, recent work has emphasized the theoretical and practical importance of the relationships among ecosystem services, which may range from synergistic via neutral to conflicting and change in response to management (Bennett et al. 2009; Carpenter et al. 2009; Raudsepp-Hearne et al. 2010). In particular, trade-offs between provisioning and other services have been suggested to be common and driven by management that aims to maximize production (Millennium Ecosystem Assessment 2005). The main goal of forest management in commercial forestry in the boreal zone is typically to maximize timber production, as timber is the only or the primary source of revenue from the forest to the landowner. However, if management focuses disproportionately on this productive function, other important benefits may be degraded or lost.

Boreal countries are committed to sustainable management of forests and to the preservation of forest services, e.g., through the EU Forestry Strategy, the Montréal Process,[2] and the Convention on Biological Diversity.[3] The long history of forestry in boreal countries means that there are well-established systems of and accrued expertise in forest management, which may be seen as an opportunity for the development and implementation of management practices that promote diverse benefits and biodiversity (Moen et al. 2014). However, debate on the most beneficial forest management methods is ongoing, and important information is still lacking (Kuuluvainen et al. 2012). The forest models and indicators of sustainable forest management that are currently used as management and policy tools describe several forest ecosystem services insufficiently (MCPFE 2002; Mäkelä et al. 2012). Yet, forest structure, function, and biodiversity, which are all modified by forest management, are linked to the total supply of ecosystem services (Thompson et al. 2011). It is clear that the effects of forest management may extend to the level of multiple goods and services provided by the system, and because of the extent of forestry in boreal countries, the preservation of forest ecosystem services is dependent on production forests (Kuuluvainen 2009; Mönkkönen et al. 2011).

There is an abundance of empirical research on the effects of boreal forestry on certain ecosystem functions and properties, such as hydrology and soil conditions (Kreutzweiser et al. 2008), disturbance dynamics (Kuuluvainen 2009), stand structure (Brassard and Chen 2006), and certain species groups (e.g., Niemelä 1997). However, a comprehensive overview of the implications of these effects in terms of ecosystem services has to our knowledge not been performed. This is contrary to, for example, the environmental impacts of tropical forestry (e.g., Edwards et al. 2014) or agriculture (e.g., Power 2010).

In this paper, we review and synthesize our current knowledge on the environmental and social impacts of boreal forestry by applying the ecosystem services framework. The aims of this paper are (1) to investigate the previous use and potential applicability of the ecosystem services framework in this context, (2) to review the impacts intensive forestry may have by assembling literature on a range of well-acknowledged forest ecosystem services, and (3) to identify the ecosystem services and the aspects of the forestry–ecosystem services relationship that are still poorly known. As this is a wide range of issues and the space here is limited, our goal is to provide an overview of boreal forestry's potential effects on ecosystem services, rather than to survey the entire literature for quantitative estimates of the overall magnitude of these effects.

We first briefly discuss how the environmental impacts of boreal production forestry may be fitted into the ecosystem services framework and assess how widely the framework has been used in this context. Next, we describe the links between common forest management practices and a range of ecosystem services. Following the classification of the Millennium Ecosystem Assessment (2005), we present examples of forestry's impacts on regulating services (climate change mitigation, maintenance of soil productivity and water quality, resistance to natural hazards, and pollination), provisioning services (non-timber forest products), and cultural services (recreation, landscape aesthetics, and sociocultural values). We note that the environmental impacts of forestry include various effects generated during the entire life cycle of forest products, but here we focus on changes to the structure and functioning of the forest ecosystem that may, in turn, affect the supply of ecosystem services from the forest. We also

[2] http://www.montrealprocess.org/.

[3] http://www.cbd.int/.

note that biodiversity is sometimes considered an ecosystem service in itself, for example, with cultural value (Mace et al. 2012). Here, we consider biodiversity as a quality of the ecosystem, which contributes—often fundamentally—to ecosystem functioning and provision of ecosystem services (Cardinale et al. 2012; Harrison et al. 2014). Finally, we discuss the emerging patterns and the potential contribution of the ecosystem service framework with respect to sustainable forest management as well as recommendations for future research efforts.

BOREAL FORESTRY IN THE ECOSYSTEM SERVICES FRAMEWORK

Introduction to boreal production forestry

The circumpolar boreal zone is the most northerly of the world's major terrestrial biomes, encompassing about 1.890 billion ha of land mainly located within Russia, North America, and Fennoscandia (Brandt et al. 2013). The boreal zone is characterized by forests, which throughout the zone share several environmental characteristics and similar taxa. However, there is some variation within the region in the management history and current state of the forests: in Fennoscandia, boreal forests have been harvested for longer and more intensively than forests in North America and Siberia (Ruckstuhl et al. 2008; Elbakidze et al. 2013), and there is considerably less primary forest left in northern European countries than in the rest of the boreal zone (Table 1). In Canada, much of the timber harvesting is currently done in primary forests (Conference Board of Canada 2013). In northern Europe, most forests are privately owned, whereas in Canada and Russia, most forests are owned by the state or other communities (Brandt et al. 2013; Elbakidze et al. 2013).

The predominant means of timber production in boreal forests is based on clear-cut harvesting of even-aged stands. After a clear-cut, the stand is regenerated either naturally or artificially by seeding or planting. Before regeneration, the site is often prepared mechanically or by prescribed burning to ensure the establishment of a new stand. Under intensive management, regeneration may be followed by pruning and thinning of the developing stand to promote tree growth, and growth conditions may be improved by fertilization. The time of the final harvest may be determined by a planned schedule or a desired timber stock, and may aim at optimal cutting at the stand's maximal growth or at efficiency of operations over a larger area. Harvest residues and stumps may also be collected. Dead or living retention trees may be left in the logged area to promote biodiversity and soil nutrients. Forestry planning thus comprises the selection of silvicultural treatments applied to the site as well as the size, timing, and arrangement of harvests across the landscape. It is influenced by the conditions of the stands, including their accessibility, and the aims of the forest manager. In general, due to factors like management history and ownership structure, forest management in northern Europe is characterized by intensive management of relatively small stands, and in North America and Russia by extensive harvesting of larger areas (Gauthier et al. 2015). Besides clear-cutting regimes, alternative forest management systems such as those based on selection harvesting are used to a lesser extent, but interest in these systems is growing due to environmental and social concerns related to even-aged forestry (e.g., Kuuluvainen et al. 2012).

Table 1 Forest statistics of boreal countries (data from FAO 2015). It should be noted that these country-level statistics may include other forest types besides boreal forest

	Forest area (1 000 000 ha)	Forest of land area (%)	Primary forest (% of forest area)	Forest within protected areas (% of forest area)
Finland	22.2	73.1	1.0	17.7
Norway	12.1	39.8	1.3	4.8
Russia	814.9	49.8	33.5	2.2
Sweden	28.1	68.4	8.6	7.1
Canada	347.1	38.2	59.3	6.9

Delivery of forest ecosystem services

Understanding the effects of human activities on ecosystem services requires knowledge of the ecosystem processes producing the services as well as methods to quantitatively assess the state of the service supply. In general, the delivery of ecosystem services may be described as a process originating in the interactions among living organisms and their environment, leading to relevant ecosystem structures and functions, and ending with the benefits and values experienced by humans. This conceptualization is referred to as the cascade model (Haines-Young and Potschin 2010). In reality, the processes described by the model are not linear, and the stages defined in it are interconnected; however, it provides a typology for analyzing the links between ecosystem properties and human well-being in a systematic way (Haines-Young and Potschin 2010). As described above, intensive forestry comprises several management actions applied to forests throughout a rotation. These alter the biotic and abiotic structures of the forest ecosystem with potential impacts cascading through species communities, ecosystem functions, and the benefits obtained by humans. The effects of forest management on ecosystem services may thus also be comprehensively depicted and analyzed in terms of the cascade model (Fig. 1).

Indicators of ecosystem services may be defined based on any of the stages of ecosystem service generation, as enabled by the understanding of the phenomena or availability of data (Fig. 1) (e.g., Mononen et al. 2016). It may be recommendable to develop and use indicators that describe the state of ecosystem service supply at every step of their generation, because this can provide a more balanced and reliable view of the phenomenon than a single indicator, especially for monitoring and impact assessment purposes (Mononen et al. 2016). Quantification of the losses or gains in ecosystem services caused by forest management requires indicators that are intricate enough to capture the variation created by management at the different stages of ecosystem service delivery. Ideally, the effects of forest management should also be monitored or modeled over several decades or entire stand rotations, because a forest provides different ecosystem services depending on its age and structure (Schwenk et al. 2012; Zanchi et al. 2014).

Ecosystem services and boreal forestry in existing literature

The environmental impacts of boreal forestry have long been a subject of research and there are large amounts of published literature on some of these impacts, also with respect to the implications to human benefits (e.g., Webster et al. 2015; Roberge et al. 2016). In order to produce estimates of how widely boreal forestry's impacts on different ecosystem services have been studied, we conducted the literature searches in the ISI Web of Science database using search terms related to boreal forestry and different ecosystem services and recorded the numbers of results returned by each search (see Online Appendix S1 for the full list of search terms and further details). We then filtered these search results with the additional search term "ecosystem service*" to estimate how widely the concept of ecosystem services has been used in this field. The results of these simple searches indicate that there is great variation in the amount of existing literature among the different ecosystem services (Fig. 2). The numbers of articles related to maintenance of soil productivity, regulation of water flow and quality, and climate regulation are manifold compared with, for example, resistance to natural hazards, pollination, or provision of non-timber forest products. In addition, by filtering this literature with the search term "ecosystem service*", it becomes apparent that the use of the ecosystem service terminology has so far been marginal in this context (Fig. 2). This finding is supported by the extensive review by Abson et al. (2014), who reported ecosystem service literature from forest ecosystems to be focused on tropical forests. Few, model-based studies have examined the effects of boreal forest management on ecosystem services (Miina et al. 2010; Zanchi et al. 2014; Triviño et al. 2017), but the set of

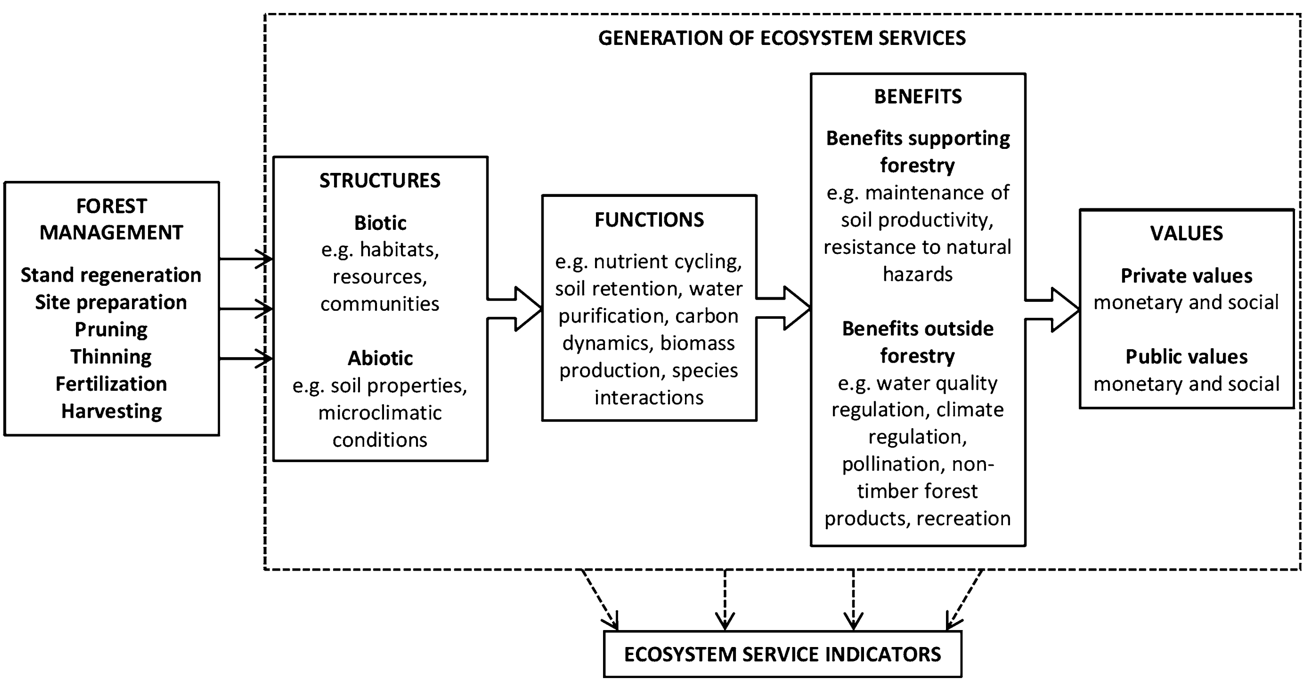

Fig. 1 Framework linking forest management activities via forest structures and functions to final benefits and values experienced by humans. Indicators of ecosystem service supply may be defined based on all of the four stages of ecosystem service generation

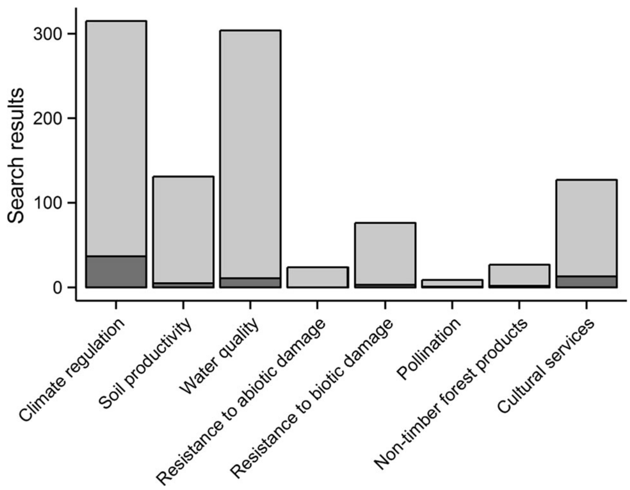

Fig. 2 Numbers of results returned by the literature searches using search strings related to boreal forestry and different phenomena associated with specific ecosystem services. Each ecosystem service had its own predefined set of search terms. The dark grey part of each bar shows the portion of the search results returned when the additional search term "ecosystem service*" was used. A detailed description of the literature searches, including a full list of search terms, is given in Online Appendix S1

ecosystem services included also in these studies is limited compared with the wide range of benefits that boreal forests provide. It is clear that the existing literature, particularly literature building on the ecosystem services framework, does not yet cover the full range of boreal forestry's potential consequences for human benefits.

EFFECTS OF FOREST MANAGEMENT ON ECOSYSTEM SERVICES

Regulating services

The role of boreal forests in climate regulation is one of their most widely studied functions. "The second lung of the planet" (Warkentin and Bradshaw 2012), boreal forest, contributes greatly to global air-quality and climate regulation. Carbon storage and sequestration by boreal forests is hugely important for global climate change mitigation (Pan et al. 2011), but the effects of forestry on these functions are complex. Forestry has a negative impact on climate change mitigation if it decreases the system's ability to fix carbon or if it results in releases of carbon into the atmosphere from long-term storages in the forest ecosystem, for example via disturbances to soils where most of the carbon resides (Jandl et al. 2007; Bradshaw and Warkentin 2015). Conversely, human interference may safeguard carbon storage, e.g., by preventing forest fires (Kurz et al. 2008), and forest management may increase carbon sequestration, e.g., by promoting tree growth via tree species choice or fertilization (Hyvönen et al. 2007). Whether production forests act as carbon sources or sinks may critically depend on the fate of the carbon fixed in harvested wood products (Liski et al. 2001). Moreover, forests contribute to climate regulation in other ways besides carbon dynamics, such as surface albedo (Lutz and Howarth 2014) and production of aerosols that contribute to cloud formation (Spracklen et al. 2008). The total effect of forest management on climate regulation is thus a result of several complex processes, many of which remain poorly understood.

At local scales, some of the most important ecosystem services from forests are related to water and soil quality. As shown above, these are also some of the most widely studied forest functions. Forest vegetation retains water, nutrients, and soil, both maintaining the productivity of the soil and regulating the quality of adjacent waters. In terms of nutrient cycling, undisturbed boreal forests are a comparatively closed system, and naturally occurring nutrient leaching from boreal forests is relatively low (Mattsson et al. 2003; Maynard et al. 2014). Forestry activities have direct impacts on soil physical properties and decomposer communities, alter the conditions in the forest, and disturb the nutrient cycling processes, and may thus change the ability of the forest to maintain soil productivity (Grigal 2000; Kreutzweiser et al. 2008; Hartmann et al. 2012). Harvesting, fertilization, and soil preparation activities typically increase nutrient availability and loss by leaching (Mattsson et al. 2003; Kreutzweiser et al. 2008), and road construction and use of heavy machinery may increase erosion and reduce the productivity of the site (Grigal 2000). In addition, nutrients are lost from managed forests in harvested biomass, with the amount of nutrients lost depending on harvesting intensity. Nutrient losses caused by biomass removal and increased leaching are variable, but have in many cases been estimated to be small in effect, and boreal forest soils appear to recover from them relatively rapidly (Kreutzweiser et al. 2008). However, forestry operations also have effects on soils that are not yet fully understood, such as changes in the composition of soil communities. These changes may, in fact, be more persistent than changes in soil nutrient pools, but their functional implications remain to be determined (Hartmann et al. 2012).

The consequences of reduced nutrient retention capacity in managed forests may be greater for water quality than those for soil fertility (Kreutzweiser et al. 2008; Webster et al. 2015). Nutrient and organic matter loads from forestry contribute to water eutrophication and increased turbidity, and some forestry operations may increase the transport of toxic compounds like methyl mercury into surface waters (Webster et al. 2015). Out of all silvicultural operations, clear-cut harvesting combined with mechanical site preparation is considered to have the strongest effect on runoff water quantity and quality, but the magnitude of the effect is heavily site dependent (Kreutzweiser et al. 2008). Because forests can retain nutrients arriving from upstream sources, leaving unfelled forests as buffers between waters and clear-cuts can be an effective way to mitigate the effects of forestry on water quality (Gundersen et al. 2010), although their effectiveness may depend on factors like the intensity of harvesting and the exact configuration of hydrologic pathways (Webster et al. 2015). Indeed, forests act as water-quality regulators most importantly when they are adjacent to waters and can act as buffer zones, or when they grow on nutrient-rich sites where the potential for nutrient leaching is high. In these sites, activities that reduce the forest's nutrient-retention ability may cause the most substantial losses in the service of water-quality regulation.

Besides regulation of climate, water, and soils, forest ecosystems perform functions that regulate the occurrence of natural disturbances. Natural disturbances to forests are biotic (pests and pathogens) and abiotic (fire, wind, floods) hazards that severely alter forest structure and function (Jactel et al. 2009). Resistance to natural disturbances and mitigation of their effects may be considered as ecosystem services that protect the timber stock. By regulating stand structure, tree age distribution, species composition, and tree growth, forest management may significantly alter the forest's susceptibility to both biotic and abiotic hazards (Schelhaas et al. 2003; Jactel et al. 2009). For instance, resistance to wind damage may be reinforced by planning stand rotations to smooth out height ratios among neighboring forest stands (Zeng et al. 2009), and by planning clear-cut size, placement, and density over the landscape to reduce the total length of stand edges (Zeng et al. 2010). Biotic hazards may be mitigated by minimizing the availability of alternative food and breeding resources of pest species (Jactel et al. 2009). Natural resistance to pests and pathogens may also be increased by managing stand composition to create natural barriers or by providing resources for natural control agents (Jactel et al. 2009). Increased stand diversity is often presented as a way to promote stand resistance to pests, but such effects in boreal forests have been questioned due to lack of empirical evidence (Koricheva et al. 2006).

Overall, production forests offer habitats for a range of beneficial organisms that provide important regulating services, such as natural enemies of pests, pollinators, and decomposers. These are the forest ecosystem services that seem to be the least studied and the most poorly understood, especially with respect to their responses to forest management. For example, it is suggested that predators such as three-toed woodpeckers (*Picoides tridactylus*) may contribute to stabilizing the population dynamics of forest pests, but their ability to do so depends on complex multiscale interactions that are not fully understood (Fayt et al. 2005). Pollinators inhabiting production forests contribute to the production of forest berries and to crop production in adjacent agricultural areas. In Finland, for example, pollination of several agricultural crops and forest berries is heavily dependent on bumblebees, and, despite extensive forestry, the Finnish forest-inhabiting bumblebee species populations are estimated stable or increasing (Paukkunen et al. 2007). However, lack of natural disturbances and the nesting resources that disturbances create has been also suggested to negatively affect pollinators (Rodríguez and Kouki 2015). Taki et al. (2011) found forest management to reduce the habitat and resource quality of forests and, in turn, the presence and abundance of pollinators in adjacent areas in an agriculturally dominated landscape in Japan. However, these relationships seem not to have been studied in the boreal region. Information is thus lacking on the effects of forest management on local populations of pollinators as well as other beneficial organisms.

Provisioning and cultural services

Production forests are a source of several products besides timber, such as berries, mushrooms, and herbs, collectively termed non-timber forest products. These products may have great economic and cultural importance especially in Aboriginal and rural communities (Duchesne and Wetzel 2002). Several factors independent of forest management affect the abundance of non-timber forest products, such as site type, climate, and weather conditions (e.g., Miina et al. 2009; Turtiainen et al. 2013). However, several forest characteristics that are altered by management, such as tree species composition, canopy openness, understory vegetation, and soil structure, moisture, and nutrient status (discussed above), also affect the suitability of a site as a habitat for species, and thus the availability of related products for humans (Miina et al. 2009; Gamfeldt et al. 2013). These effects may be positive or negative; for example, clear-cut harvesting has been reported to increase (Nybakken et al. 2013) or decrease (Atlegrim and Sjöberg 1996) the abundance of bilberry (*Vaccinium myrtillus*), depending on the characteristics of the site. Naturally the direction of these effects depends also on the requirements of the focal species. When the non-timber forest products are from species that thrive in young stands or benefit from increased canopy openness, their production may be particularly compatible with production forestry (e.g., Clason et al. 2008).

Abundance of several non-timber forest products is a component of cultural ecosystem services because of the high recreational and cultural value of activities like berry picking. Forests also offer opportunities for several other recreational and educational activities such as hiking, camping, and wildlife observation (Vanhanen et al. 2012). Where there is public access to production forests (e.g., the so-called "everyman's right" in Finland, Norway, and Sweden), they may be traditionally highly valued as a source of recreation (Parviainen 2015). Landscapes viewed as attractive or natural also have recreational and cultural value as such (Millennium Ecosystem Assessment 2005). Cultural services are often considered to be some of the most challenging ecosystem services to measure, and even though they appear to be among the most widely studied within boreal forests (Fig. 2), this literature reflects the complexity of the matter. For example, the recreational and scenic value of forest landscapes depends on individual preferences that may be variable. However, a review of preference surveys from the northern Europe concluded that factors such as accessibility, naturalness, and biodiversity typically increase the experience of recreational and aesthetic value, whereas obvious signs of forestry operations reduce it (Gundersen and Frivold 2008).

Production forests also have sociocultural value to forest owners and other stakeholders that may be affected by management and policy. In Finland, for example, the top-down instituted 'scientific' forest management in the mid-20th century led to dissent from forest owners because it conflicted with their economic interests, experience of independence, and aesthetic and cultural values attached to their forests (Siiskonen 2007). Many aspects of Aboriginal cultures depend in distinctive ways on forests and access to diverse forest lands and resources (e.g., in Canada; Sherry et al. 2005). To address this, forest planning and management systems may be developed to better incorporate Aboriginal interests and traditions (e.g., Wyatt 2008; Asselin et al. 2015).

DISCUSSION

In boreal production forests, the main focus of management is usually to enhance timber production. Our review suggests that intensive production forestry may have substantial effects on numerous ecosystem services (Fig. 3), and that these effects may be harmful or beneficial (Table 2). As described by the cascade model (Haines-Young and Potschin 2010), these effects are the result of changes caused by forestry to forest structures and functions that underpin ecosystem services. The evaluation of these changes from the perspective of ecosystem services is an emerging research path that may provide valuable insights for sustainable forest management. In order to do so, it must aim at clarifying the numerous ecological processes involved in the forestry–ecosystem services relationship that are still poorly understood (Mori et al. 2016), as well as the social processes that influence forest management decisions, demand for non-timber forest benefits, and the valuation of these benefits (Sandström et al. 2011; Filyushkina et al. 2016).

Overall, the forest's capacity to provide ecosystem services appears to be typically weakened when forestry activities are intensive and disturbances to the natural state and functioning are acute and severe. The extent and intensity of harvesting and site preparation seem to be among the most important management choices, as these operations have major potential for deteriorating several services simultaneously (e.g., climate regulation, maintenance of soil productivity, regulation of water quality, storm damage resistance, and aesthetic values). In addition to the harvesting method, tree species selection, thinning intensity, and regeneration method fundamentally affect the structure of the forest with impacts on, for example, habitat suitability for pollinators, abundance of forest collectables, and recreational attractiveness. In some situations, forest management may enhance the supply of an ecosystem service compared with the natural state, e.g., by creating suitable habitat for desired organisms. Identifying the forestry practices that contribute the most to the deterioration of ecosystem services and the types of forest sites that are particularly vulnerable to them are important research avenues that can inform the development of management practices that support production forests' role as ecosystem service providers (cf. Sandström et al. 2011; Edwards et al. 2014; Filyushkina et al. 2016). In order to secure diverse ecosystem services from forests, the suitability of management options to different stands and landscapes should be evaluated using broad criteria and long-term impact assessments (Laudon et al. 2011; Schwenk et al. 2012; Mönkkönen et al. 2014; Asselin et al. 2015).

Among the ecosystem services we reviewed, the least well understood with respect to forestry's potential impacts on them are the maintenance of soil productivity by soil communities, natural pest control, and pollination (Fig. 2). The existing literature on the impacts of boreal forestry on ecosystem services and related ecosystem functions is dominated by biophysical processes such as soil conditions, hydrology, and carbon storage and sequestration. Despite calls for research that would shed light on the ecological basis of ecosystem services (e.g., Kremen 2005), substantial knowledge gaps remain about the role of community structure in ecosystem functions and the provision of ecosystem services in forests (Mori et al. 2016). As a consequence, even though the negative impacts of boreal forestry on biodiversity are established for several species groups (e.g., Niemelä 1997; Venier et al. 2014), the implications of this biodiversity loss for the supply of forest ecosystem services are still poorly understood. The

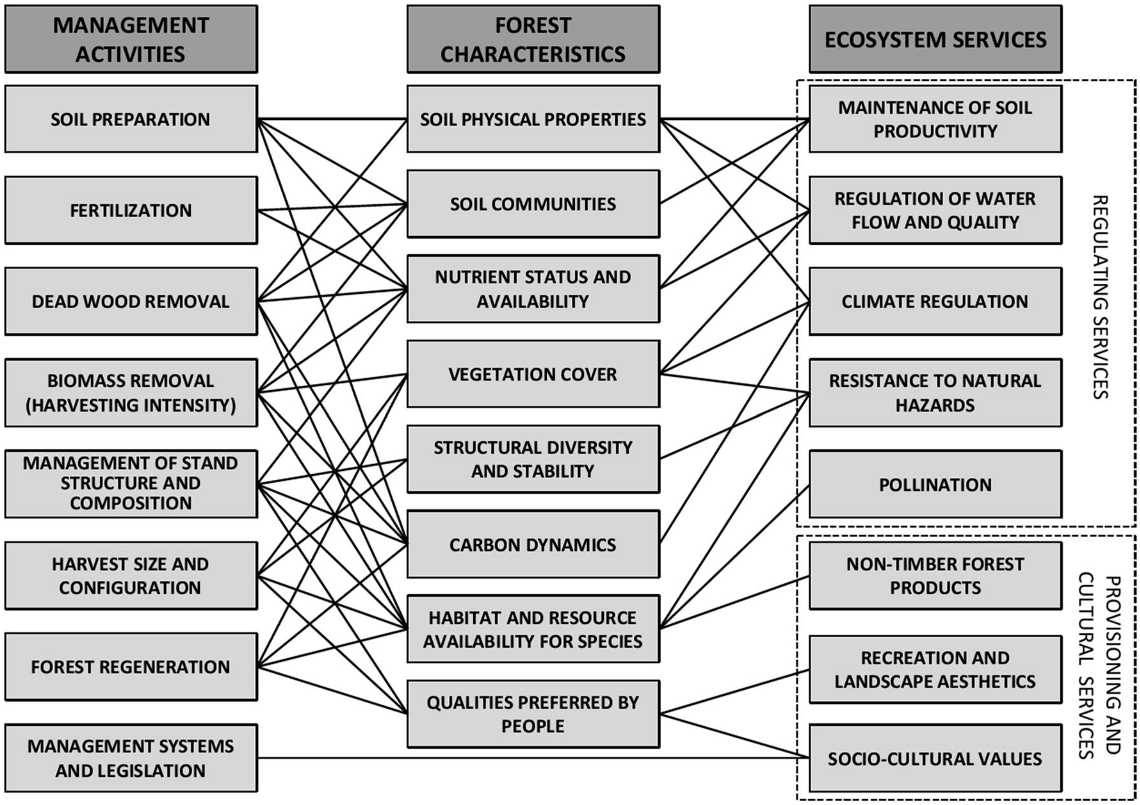

Fig. 3 Summary of some of the main connections between forest management activities, forest characteristics, and ecosystem services. *Lines connecting the boxes* in the columns show the impacts of management via forest characteristics on ecosystem services. These connections also show how identification and assessment of ecosystem services may guide management choices

Table 2 Changes in the supply of forest ecosystem services caused by production forestry as compared with undisturbed forest based on an overview of existing literature. Downward arrows indicate negative changes and upward arrows positive changes

Ecosystem service	Reported impacts
Maintenance of soil productivity	↑, ↓
Regulation of water flow and quality	↓
Climate regulation	↑, ↓
Resistance to biotic hazards	↓
Resistance to abiotic hazards	↓
Pollination	↑
Non-timber forest products	↑, ↓
Cultural services	↑, ↓

links between the diversity of forest communities and the maintenance of ecosystem services should be a major focus of future work (Thompson et al. 2011; Mori et al. 2016). Many ecosystem services are the product of complex ecological processes (as described by the cascade model), and it seems typical that forestry's effects on one or a few components of these processes are understood, but the overall effect on the final ecosystem service and the benefits and values derived by humans is not. This is the case even for the most widely studied ecosystem services, such as climate regulation (Landry and Ramankutty 2015). In addition, uncertainties remain about the long-term ability of the actively harvested and managed forests to provide also the widely studied ecosystem services, for example, regulation of water quality (Webster et al. 2015). Across various contexts, a good understanding of ecosystem service provision and its response to ecosystem change over different spatial and temporal scales is still lacking (Biggs et al. 2012; Mace et al. 2012).

Trade-offs between provisioning and other services are suggested to be frequent (Millennium Ecosystem Assessment 2005; Carpenter et al. 2009; Raudsepp-Hearne et al. 2010; Gamfeldt et al. 2013), and in production forests this situation is realized in the cases where activities intended to increase timber harvests cause other ecosystem services to deteriorate. These trade-offs may become more severe in the upcoming decades in response to the efforts to raise wood production to increasingly replace fossil fuels with forest energy and to sustain the demand for new wood-fiber based products and bio-materials. Whether this is achieved by subjecting more forest areas to harvesting, increasing forest productivity, or increasing the amount of biomass harvested, there are likely to be consequences in terms of the supply of forest ecosystem services. For example, increased biomass harvesting may lead to increasingly consequential nutrient losses from the system (Kreutzweiser et al. 2008), causing decreases in soil productivity and carbon sequestration capacity. With careful planning, however, it may be possible to design forest management to mitigate the trade-offs and promote the win–win situations among various objectives. This may require increased diversity in the adopted management regimes (e.g., Kuuluvainen et al. 2012) and care in the application of management activities to explicitly target multiple ecosystem services (e.g., Triviño et al. 2017).

Even though there is a long research tradition of linking forestry with ecosystem functioning, the terminology of ecosystem services has so far been used only marginally in the context of assessing the environmental impacts of boreal forestry. This is contrary to its common adoption in policy (e.g., the EU Forestry Strategy) and its rapidly growing use in other academic literature (Abson et al. 2014). The advantages and disadvantages of the concept are under ongoing debate (see e.g., Schröter et al. 2014). However, its widespread use suggests that at least some of its merits are widely accepted and that it is seen as policy relevant (e.g., Thompson et al. 2011). If the merits of the ecosystem services framework are accepted then its application in the context of boreal forestry is highly appropriate. It is based on a holistic socioecological system approach (Millennium Ecosystem Assessment 2005; Bennett et al. 2009; Carpenter et al. 2009), and may thus be well suited for analyzing the environmental impacts of forestry that are variable in direction, intensity, scale, and persistence. Boreal production forests are often associated with strong cultural values and identities by local people and play crucial roles in global biophysical processes. Therefore, evaluation of forestry's impacts on forest communities and ecosystem functions from the perspective of human benefits and values may be considered relevant in this context. Central to the ecosystem service approach is that it links ecosystem function and condition directly to the interests of different stakeholder groups and to political decision-making (Thompson et al. 2011), and may guide and promote conservation of taxa and ecosystems that may otherwise be overlooked (Mori et al. 2016). The concept has an inherent aim of advancing the sustainability of natural resource use (Millennium Ecosystem Assessment 2005). Thus, it is relevant with respect to developing sustainable forest management, which aims to reconcile multiple interests related to forests (Rametsteiner and Simula 2003; Mäkelä et al. 2012). Then again, it is worth noting that the ecosystem services approach is only one way to describe human–environment relationships and that additional or alternative formulations can be more advantageous, depending on the aims and the situation (Raymond et al. 2013). Researchers using the ecosystem service terminology should be aware of its implicit assumptions and the limitations that come with them (Raymond et al. 2013; Schröter et al. 2014).

An important issue that is beyond the scope of this work is the preservation of biodiversity in boreal forests. Biodiversity may co-occur with or fundamentally underlie ecosystem services, but these links are not guaranteed, especially for all services and all aspects of biodiversity (Mace et al. 2012; Harrison et al. 2014). In the upcoming decades, the management choices concerning boreal forests will likely have crucial implications to global efforts of biodiversity conservation (Moen et al. 2014). In order to secure preservation of boreal biodiversity and to meet international conservation targets, impacts on biodiversity must also be taken into account in the planning and evaluation of forest management strategies.

The multiple pressures facing boreal production forests are likely to intensify in the upcoming decades. In addition to production objectives and forest management choices, the future of forest ecosystem services depends on climate change and its effects. This myriad of intensifying, interconnected environmental and socioeconomic pressures facing boreal forests poses a great challenge to their management. The state of existing literature suggests that the framework of ecosystem services has so far been used in the context of boreal forestry to a very limited extent. However, it may be considered very applicable in this context because of the diverse benefits boreal forests provide globally as well as locally, and because, as this review shows, the supply of these benefits can be greatly affected by forest management actions. Major knowledge gaps remain regarding these processes, and we highlight especially the following research needs:

- The role of biodiversity and community structure in ecosystem functions and the generation of forest ecosystem services
- Impacts of biodiversity loss on the provision of forest ecosystem services
- Impacts of forestry on the long-term resilience of forest functions and the sustained supply of ecosystem services
- The drivers of demand for diverse forest ecosystem services
- Management strategies to balance conflicting demands and policy tools to implement them.

These issues mirror research needs identified by other authors (Moen et al. 2014; Filyushkina et al. 2016; Mori et al. 2016). By addressing these open questions, the ecosystem service approach may be a valuable tool in assessing the sustainability of forestry practices and in resolving conflicts between the various interests related to boreal forests.

Acknowledgments We are grateful to the Kone Foundation and to the Academy of Finland (Project Number 275329 to M. Mönkkönen) for funding.

REFERENCES

Abson, D.J., H. von Wehrden, S. Baumgärtner, J. Fischer, J. Hanspach, W. Härdtle, H. Heinrichs, A.M. Klein, et al. 2014. Ecosystem services as a boundary object for sustainability. *Ecological Economics* 103: 29–37. doi:10.1016/j.ecolecon.2014.04.012.

Asselin, H., M. Larouche, and D. Kneeshaw. 2015. Assessing forest management scenarios on an Aboriginal territory through simulation modeling. *Forestry Chronicle* 91: 426–435. doi:10.5558/tfc2015-072.

Atlegrim, O., and K. Sjöberg. 1996. Response of bilberry (*Vaccinium myrtillus*) to clear-cutting and single-tree selection harvests in uneven-aged boreal *Picea abies* forests. *Forest Ecology and Management* 86: 39–50. doi:10.1016/S0378-1127(96)03794-2.

Bennett, E.M., G.D. Peterson, and L.J. Gordon. 2009. Understanding relationships among multiple ecosystem services. *Ecology Letters* 12: 1394–1404. doi:10.1111/j.1461-0248.2009.01387.x.

Biggs, R., M. Schlüter, D. Biggs, E.L. Bohensky, S. BurnSilver, G. Cundill, V. Dakos, T.M. Daw, et al. 2012. Toward principles for enhancing the resilience of ecosystem services. *Annual Review of Environment and Resources* 37: 421–448. doi:10.1146/annurev-environ-051211-123836.

Bradshaw, C.J.A., and I.G. Warkentin. 2015. Global estimates of boreal forest carbon stocks and flux. *Global and Planetary Change* 128: 24–30. doi:10.1016/j.gloplacha.2015.02.004.

Bradshaw, C.J.A., I.G. Warkentin, and N.S. Sodhi. 2009. Urgent preservation of boreal carbon stocks and biodiversity. *Trends in Ecology & Evolution* 24: 541–548. doi:10.1016/j.tree.2009.03.019.

Brandt, J.P., M.D. Flannigan, D.G. Maynard, I.D. Thompson, and W.J.A. Volney. 2013. An introduction to Canada's boreal zone: Ecosystem processes, health, sustainability, and environmental issues. *Environmental Reviews* 21: 207–226. doi:10.1139/er-2013-0040.

Brassard, B.W., and H.Y.H. Chen. 2006. Stand structural dynamics of North American boreal forests. *Critical Reviews in Plant Sciences* 25: 115–137. doi:10.1080/07352680500348857.

Cardinale, B.J., J.E. Duffy, A. Gonzalez, D.U. Hooper, C. Perrings, P. Venail, A. Narwani, G.M. Mace, et al. 2012. Biodiversity loss and its impact on humanity. *Nature* 486: 59–67. doi:10.1038/nature11148.

Carpenter, S.R., H.A. Mooney, J. Agard, D. Capistrano, R.S. DeFries, S. Díaz, T. Dietz, A.K. Duraiappah, et al. 2009. Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proceedings of the National academy of Sciences of the United States of America* 106: 1305–1312. doi:10.1073/pnas.0808772106.

Clason, A.J., P.M.F. Lindgren, and T.P. Sullivan. 2008. Comparison of potential non-timber forest products in intensively managed young stands and mature/old-growth forests in south-central British Columbia. *Forest Ecology and Management* 256: 1897–1909. doi:10.1016/j.foreco.2008.07.013.

Conference Board of Canada. 2013. Use of Forest Resources. Retrieved 23 September, 2015, from http://www.conferenceboard.ca/hcp/details/environment/use-of-forest-resources.aspx.

Costanza, R., R. D'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, et al. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387: 253–260. doi:10.1038/387253a0.

Duchesne, L.C., and S. Wetzel. 2002. Managing timber and non-timber forest product resources in Canada's forests: Needs for integration and research. *The Forestry Chronicle* 78: 837–842. doi:10.5558/tfc78837-6.

Edwards, D.P., J.A. Tobias, D. Sheil, E. Meijaard, and W.F. Laurance. 2014. Maintaining ecosystem function and services in logged tropical forests. *Trends in Ecology & Evolution* 29: 511–520. doi:10.1016/j.tree.2014.07.003.

Elbakidze, M., K. Andersson, P. Angelstam, G.W. Armstrong, R. Axelsson, F. Doyon, M. Hermansson, J. Jacobsson, et al. 2013. Sustained yield forestry in Sweden and Russia: How does it correspond to sustainable forest management policy? *Ambio* 42: 160–173. doi:10.1007/s13280-012-0370-6.

FAO (Food and Agriculture Organization of the United Nations). 2015. Global Forest Resources Assessment 2015. Desk reference. FAO, Rome, Italy

Fayt, P., M.M. Machmer, and C. Steeger. 2005. Regulation of spruce bark beetles by woodpeckers—A literature review. *Forest Ecology and Management* 206: 1–14. doi:10.1016/j.foreco.2004.10.054.

Filyushkina, A., N. Strange, M. Löf, E.E. Ezebilo, and M. Boman. 2016. Non-market forest ecosystem services and decision support in Nordic countries. *Scandinavian Journal of Forest Research* 31: 99–110. doi:10.1080/02827581.2015.1079643.

Gamfeldt, L., T. Snäll, R. Bagchi, M. Jonsson, L. Gustafsson, P. Kjellander, M.C. Ruiz-Jaen, M. Fröberg, et al. 2013. Higher levels of multiple ecosystem services are found in forests with more tree species. *Nature Communications* 4: 1340. doi:10.1038/ncomms2328.

Gauthier, S., P. Bernier, T. Kuuluvainen, A.Z. Shvidenko, and D.G. Schepaschenko. 2015. Boreal forest health and global change. *Science* 349: 819–822. doi:10.1126/science.aaa9092.

Grigal, D.F. 2000. Effects of extensive forest management on soil productivity. *Forest Ecology and Management* 138: 167–185. doi:10.1016/S0378-1127(00)00395-9.

Gundersen, V.S., and L.H. Frivold. 2008. Public preferences for forest structures: A review of quantitative surveys from Finland, Norway and Sweden. *Urban Forestry & Urban Greening* 7: 241–258. doi:10.1016/j.ufug.2008.05.001.

Gundersen, P., A. Laurén, L. Finér, E. Ring, H. Koivusalo, M. Sætersdal, J.-O. Weslien, B.D. Sigurdsson, et al. 2010. Environmental services provided from riparian forests in the Nordic countries. *Ambio* 39: 555–566. doi:10.1007/s13280-010-0073-9.

Haines-Young, R.H., and M.B. Potschin. 2010. The links between biodiversity, ecosystem services and human well-being. In *Ecosystems ecology: A new synthesis*, ed. D.G. Raffaelli, and C.L.J. Frid. Cambridge: Cambridge University Press.

Harrison, P.A., M. Vandewalle, M.T. Sykes, P.M. Berry, R. Bugter, F. de Bello, C.K. Feld, U. Grandin, et al. 2010. Identifying and prioritising services in European terrestrial and freshwater ecosystems. *Biodiversity and Conservation* 19: 2791–2821. doi:10.1007/s10531-010-9789-x.

Harrison, P.A., P.M. Berry, G. Simpson, J.R. Haslett, M. Blicharska, M. Bucur, R. Dunford, B. Egoh, et al. 2014. Linkages between biodiversity attributes and ecosystem services: A systematic review. *Ecosystem Services* 9: 191–203. doi:10.1016/j.ecoser.2014.05.006.

Hartmann, M., C.G. Howes, D. VanInsberghe, H. Yu, D. Bachar, R. Christen, R. Henrik Nilsson, S.J. Hallam, et al. 2012. Significant and persistent impact of timber harvesting on soil microbial communities in Northern coniferous forests. *The ISME Journal* 6: 2199–2218. doi:10.1038/ismej.2012.84.

Hyvönen, R., G.I. Ågren, S. Linder, T. Persson, M.F. Cotrufo, A. Ekblad, M. Freeman, A. Grelle, et al. 2007. The likely impact of elevated [CO_2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: A literature review. *New Phytologist* 173: 463–480. doi:10.1111/j.1469-8137.2007.01967.x.

Jactel, H., B.C. Nicoll, M. Branco, J.R. Gonzalez-Olabarria, W. Grodzki, B. Långström, F. Moreira, S. Netherer, et al. 2009. The influences of forest stand management on biotic and abiotic risks of damage. *Annals of Forest Science* 66: 701. doi:10.1051/forest/2009054.

Jandl, R., M. Lindner, L. Vesterdal, B. Bauwens, R. Baritz, F. Hagedorn, D.W. Johnson, K. Minkkinen, et al. 2007. How strongly can forest management influence soil carbon sequestration? *Geoderma* 137: 253–268. doi:10.1016/j.geoderma.2006.09.003.

Koricheva, J., H. Vehviläinen, J. Riihimäki, K. Ruohomäki, P. Kaitaniemi, and H. Ranta. 2006. Diversification of tree stands as a means to manage pests and diseases in boreal forests: myth or reality? *Canadian Journal of Forest Research* 36: 324–336. doi:10.1139/x05-172.

Kremen, C. 2005. Managing ecosystem services: What do we need to know about their ecology? *Ecology Letters* 8: 468–479. doi:10.1111/j.1461-0248.2005.00751.x.

Kreutzweiser, D.P., P.W. Hazlett, and J.M. Gunn. 2008. Logging impacts on the biogeochemistry of boreal forest soils and nutrient export to aquatic systems: A review. *Environmental Reviews* 16: 157–179. doi:10.1139/A08-006.

Kurz, W.A., G. Stinson, G.J. Rampley, C.C. Dymond, and E.T. Neilson. 2008. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National academy of Sciences of the United States of America* 105: 1551–1555. doi:10.1073/pnas.0708133105.

Kuuluvainen, T. 2009. Forest management and biodiversity conservation based on natural ecosystem dynamics in Northern Europe: The complexity challenge. *Ambio* 38: 309–315. doi:10.1579/08-A-490.1.

Kuuluvainen, T., O. Tahvonen, and T. Aakala. 2012. Even-aged and uneven-aged forest management in boreal Fennoscandia: A review. *Ambio* 41: 720–737. doi:10.1007/s13280-012-0289-y.

Laudon, H., R.A. Sponseller, R.W. Lucas, M.N. Futter, G. Egnell, K. Bishop, A. Ågren, E. Ring, et al. 2011. Consequences of more intensive forestry for the sustainable management of forest soils and waters. *Forests* 2: 243–260. doi:10.3390/f2010243.

Landry, J.-S., and N. Ramankutty. 2015. Carbon cycling, climate regulation, and disturbances in Canadian forests: Scientific principles for management. *Land* 4: 83–118. doi:10.3390/land4010083.

Liski, J., A. Pussinen, K. Pingoud, R. Mäkipää, and T. Karjalainen. 2001. Which rotation length is favourable to carbon sequestration? *Canadian Journal of Forest Research* 31: 2004–2013. doi:10.1139/x01-140.

Lutz, D.A., and R.B. Howarth. 2014. Valuing albedo as an ecosystem service: Implications for forest management. *Climatic Change* 124: 53–63. doi:10.1007/s10584-014-1109-0.

Mace, G.M., K. Norris, and A.H. Fitter. 2012. Biodiversity and ecosystem services: A multilayered relationship. *Trends in Ecology & Evolution* 27: 19–26. doi:10.1016/j.tree.2011.08.006.

Maes, J., C. Liquete, A. Teller, M. Erhard, M.L. Paracchini, J.I. Barredo, B. Grizzetti, A. Cardoso, et al. 2016. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. *Ecosystem Services* 17: 14–23. doi:10.1016/j.ecoser.2015.10.023.

Mattsson, T., L. Finér, P. Kortelainen, and T. Sallantaus. 2003. Brook water quality and background leaching from unmanaged forested catchments in Finland. *Water, Air, and Soil Pollution* 147: 275–297. doi:10.1023/A:1024525328220.

Maynard, D.G., D. Paré, E. Thiffault, B. Lafleur, K.E. Hogg, and B. Kishchuk. 2014. How do natural disturbances and human activities affect soils and tree nutrition and growth in the Canadian boreal forest? *Environmental Reviews* 22: 161–178. doi:10.1139/er-2013-0057.

MCPFE (Ministerial Conference on the Protection of Forests in Europe). 2002. Improved Pan-European Indicators for Sustainable Forest Management as adopted by the MCPFE Expert Level Meeting 7-8 October 2002, Vienna, Austria. Vienna: MCPFE Liaison Unit.

Miina, J., J.-P. Hotanen, and K. Salo. 2009. Modelling the abundance and temporal variation in the production of bilberry. *Silva Fennica* 43: 577–593. doi:10.14214/sf.181.

Miina, J., T. Pukkala, J.-P. Hotanen, and K. Salo. 2010. Optimizing the joint production of timber and bilberries. *Forest Ecology and Management* 259: 2065–2071. doi:10.1016/j.foreco.2010.02.017.

Millennium Ecosystem Assessment. 2005. *Ecosystems and human well-being: Synthesis*. Washington, DC: Island Press.

Moen, J., L. Rist, K. Bishop, F.S. Chapin III, D. Ellison, T. Kuuluvainen, H. Petersson, K.J. Puettmann, et al. 2014. Eye on the Taiga: Removing global policy impediments to safeguard the boreal forest. *Conservation Letters* 7: 408–418. doi:10.1111/conl.12098.

Mononen, L., A.-P. Auvinen, A.-L. Ahokumpu, M. Rönkä, N. Aarras, H. Tolvanen, M. Kamppinen, E. Viirret, et al. 2016. National ecosystem service indicators: Measures of social–ecological sustainability. *Ecological Indicators* 61: 27–37. doi:10.1016/j.ecolind.2015.03.041.

Mori, A.S., K.P. Lertzman, and L. Gustafsson. 2016. Biodiversity and ecosystem services in forest ecosystems: A research agenda for applied forest ecology. *Journal of Applied Ecology* 54: 12–27. doi:10.1111/1365-2664.12669.

Mäkelä, A., M. del Río, J. Hynynen, M.J. Hawkins, C. Reyer, P. Soares, M. van Oijen, and M. Tomé. 2012. Using stand-scale forest models for estimating indicators of sustainable forest management. *Forest Ecology and Management* 285: 164–178. doi:10.1016/j.foreco.2012.07.041.

Mönkkönen, M., P. Reunanen, J.S. Kotiaho, A. Juutinen, O.-P. Tikkanen, and J. Kouki. 2011. Cost-effective strategies to conserve boreal forest biodiversity and long-term landscape-level maintenance of habitats. *European Journal of Forest Research* 130: 717–727. doi:10.1007/s10342-010-0461-5.

Mönkkönen, M., A. Juutinen, A. Mazziotta, K. Miettinen, D. Podkopaev, P. Reunanen, H. Salminen, and O.-P. Tikkanen. 2014. Spatially dynamic forest management to sustain biodiversity and economic returns. *Journal of Environmental Management* 134: 80–89. doi:10.1016/j.jenvman.2013.12.021.

Niemelä, J. 1997. Invertebrates and boreal forest management. *Conservation Biology* 11: 601–610. doi:10.1046/j.1523-1739.1997.06008.x.

Nybakken, L., V. Selås, and M. Ohlson. 2013. Increased growth and phenolic compounds in bilberry (*Vaccinium myrtillus* L.) following forest clear-cutting. *Scandinavian Journal of Forest Research* 28: 319–330. doi:10.1080/02827581.2012.749941.

Pan, Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, et al. 2011. A large and persistent carbon sink in the world's forests. *Science* 333: 988–993. doi:10.1126/science.1201609.

Parviainen, J. 2015. Cultural heritage and biodiversity in the present forest management of the boreal zone in Scandinavia. *Journal of Forest Research* 20: 445–452. doi:10.1007/s10310-015-0499-9.

Paukkunen, J., J. Heliölä, and M. Kuussaari. 2007. Habitats and population trends of bumblebees in Finnish agricultural environments. In *Biodiversity in Farmland*, ed. J. Salonen, M. Keskitalo, and M. Segerstedt, 289–312. Jokioinen: MTT Agrifood Research Finland. **(in Finnish, English summary)**.

Potapov, P., A. Yaroshenko, S. Turubanova, M. Dubinin, L. Laestadius, C. Thies, D. Aksenov, A. Egorov, et al. 2008. Mapping the world's intact forest landscapes by remote sensing. *Ecology and Society* 13: 51.

Power, A.G. 2010. Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 365: 2959–2971. doi:10.1098/rstb.2010.0143.

Rametsteiner, E., and M. Simula. 2003. Forest certification—An instrument to promote sustainable forest management? *Journal of Environmental Management* 67: 87–98. doi:10.1016/S0301-4797(02)00191-3.

Raudsepp-Hearne, C., G.D. Peterson, and E.M. Bennett. 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National academy of Sciences of the United States of America* 107: 5242–5247. doi:10.1073/pnas.0907284107.

Raymond, C.M., G.G. Singh, K. Benessaiah, J.R. Bernhardt, J. Levine, H. Nelson, N.J. Turner, B. Norton, et al. 2013. Ecosystem services and beyond: Using multiple metaphors to understand human-environment relationships. *BioScience* 63: 536–546. doi:10.1525/bio.2013.63.7.7.

Roberge, J.-M., H. Laudon, C. Björkman, T. Ranius, C. Sandström, A. Felton, A. Sténs, A. Nordin, et al. 2016. Socio-ecological implications of modifying rotation lengths in forestry. *Ambio* 45: S109–S123. doi:10.1007/s13280-015-0747-4.

Rodríguez, A., and J. Kouki. 2015. Emulating natural disturbance in forest management enhances pollination services for dominant *Vaccinium* shrubs in boreal pine-dominated forests. *Forest Ecology and Management* 350: 1–12. doi:10.1016/j.foreco.2015.04.029.

Ruckstuhl, K.E., E.A. Johnson, and K. Miyanishi. 2008. Introduction. The boreal forest and global change. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 363: 2245–2249. doi:10.1098/rstb.2007.2196.

Sandström, C., A. Lindkvist, K. Öhman, and E.-M. Nordström. 2011. Governing competing demands for forest resources in Sweden. *Forests* 2: 218–242. doi:10.3390/f2010218.

Schelhaas, M.-J., G.-J. Nabuurs, and A. Schuck. 2003. Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology* 9: 1620–1633. doi:10.1046/j.1365-2486.2003.00684.x.

Schröter, M., E.H. van der Zanden, A.P.E. van Oudenhoven, R.P. Remme, H.M. Serna-Chavez, R.S. de Groot, and P. Opdam. 2014. Ecosystem services as a contested concept: A synthesis of critique and counter-arguments. *Conservation Letters* 7: 514–523. doi:10.1111/conl.12091.

Schwenk, W.S., T.M. Donovan, W.S. Keeton, and J.S. Nunery. 2012. Carbon storage, timber production, and biodiversity: Comparing ecosystem services with multi-criteria decision analysis. *Ecological Applications* 22: 1612–1627. doi:10.1890/11-0864.1.

Sherry, E., R. Halseth, G. Fondahl, M. Karjala, and B. Leon. 2005. Local-level criteria and indicators: An Aboriginal perspective on sustainable forest management. *Forestry* 78: 513–539. doi:10.1093/forestry/cpi048.

Siiskonen, H. 2007. The conflict between traditional and scientific forest management in 20th century Finland. *Forest Ecology and Management* 249: 125–133. doi:10.1016/j.foreco.2007.03.018.

Spracklen, D.V., B. Bonn, and K.S. Carslaw. 2008. Boreal forests, aerosols and the impacts on clouds and climate. *Philosophical Transactions of the Royal Society. Series A: Mathematical, Physical, and Engineering Sciences* 366: 4613–4626. doi:10.1098/rsta.2008.0201.

Taki, H., Y. Yamaura, K. Okabe, and K. Maeto. 2011. Plantation vs. natural forest: Matrix quality determines pollinator abundance in crop fields. *Scientific Reports* 1: 132. doi:10.1038/srep00132.

Thompson, I.D., K. Okabe, J.M. Tylianakis, P. Kumar, E.G. Brockerhoff, N.A. Schellhorn, J.A. Parrotta, and R. Nasi. 2011. Forest biodiversity and the delivery of ecosystem goods and services: Translating science into policy. *BioScience* 61: 972–981. doi:10.1525/bio.2011.61.12.7.

Triviño, M., T. Pohjanmies, A. Mazziotta, A. Juutinen, D. Podkopaev, E. Le Tortorec, and M. Mönkkönen. 2017. Optimizing management to enhance multifunctionality in a boreal forest landscape. *Journal of Applied Ecology* 54: 61–70. doi:10.1111/1365-2664.12790.

Turtiainen, M., J. Miina, K. Salo, and J.-P. Hotanen. 2013. Empirical prediction models for the coverage and yields of cowberry in Finland. *Silva Fennica* 47: 1–22. doi:10.14214/sf.1005.

UNEP (United Nations Environment Programme), FAO (Food and Agriculture Organization of the United Nations), and UNFF (United Nations Forum on Forests Secreteriat). 2009. *Vital Forest Graphics*. UNEP/GRID-Arendal.

Vanhanen, H., R. Jonsson, Y. Gerasimov, O. Krankina, and C. Messier, ed. 2012. *Making boreal forests work for people and nature*. IUFRO.

Venier, L.A., I.D. Thompson, R. Fleming, J. Malcolm, I. Aubin, J.A. Trofymow, D. Langor, R. Sturrock, et al. 2014. Effects of natural resource development on the terrestrial biodiversity of Canadian boreal forests. *Environmental Reviews* 22: 457–490. doi:10.1139/er-2013-0075.

Vihervaara, P., T. Kumpula, A. Tanskanen, and B. Burkhard. 2010. Ecosystem services—A tool for sustainable management of human–environment systems. Case study Finnish Forest Lapland. *Ecological Complexity* 7: 410–420. doi:10.1016/j.ecocom.2009.12.002.

Warkentin, I.G., and C.J.A. Bradshaw. 2012. A tropical perspective on conserving the boreal "lung of the planet". *Biological Conservation* 151: 50–52. doi:10.1016/j.biocon.2011.10.025.

Webster, K.L., F.D. Beall, I.F. Creed, and D.P. Kreutzweiser. 2015. Impacts and prognosis of natural resource development on water and wetlands in Canada's boreal zone. *Environmental Reviews* 23: 78–131. doi:10.1139/er-2014-0063.

Wyatt, S. 2008. First Nations, forest lands, and "aboriginal forestry" in Canada: From exclusion to comanagement and beyond. *Canadian Journal of Forest Research* 38: 171–180. doi:10.1139/X07-214.

Zanchi, G., S. Belyazid, C. Akselsson, and L. Yu. 2014. Modelling the effects of management intensification on multiple forest services: A Swedish case study. *Ecological Modelling* 284: 48–59. doi:10.1016/j.ecolmodel.2014.04.006.

Zeng, H., H. Peltola, H. Väisänen, and S. Kellomäki. 2009. The effects of fragmentation on the susceptibility of a boreal forest ecosystem to wind damage. *Forest Ecology and Management* 257: 1165–1173. doi:10.1016/j.foreco.2008.12.003.

Zeng, H., J. Garcia-Gonzalo, H. Peltola, and S. Kellomäki. 2010. The effects of forest structure on the risk of wind damage at a landscape level in a boreal forest ecosystem. *Annals of Forest Science* 67: 111. doi:10.1051/forest/2009090.

AUTHOR BIOGRAPHIES

Tähti Pohjanmies (✉) is a doctoral candidate at the Department of Biological and Environmental Sciences, the University of Jyväskylä, Finland.
Address: University of Jyväskylä, Department of Biological and Environmental Sciences, P.O. Box 35, 40014 University of Jyväskylä, Finland.
e-mail: tahti.t.pohjanmies@jyu.fi

María Triviño is a post-doctoral researcher at the Department of Biological and Environmental Sciences, the University of Jyväskylä, Finland.
Address: University of Jyväskylä, Department of Biological and Environmental Sciences, P.O. Box 35, 40014 University of Jyväskylä, Finland.
e-mail: maria.m.trivino-delacal@jyu.fi

Eric Le Tortorec is a post-doctoral researcher at the Department of Biological and Environmental Sciences, the University of Jyväskylä, Finland.
Address: University of Jyväskylä, Department of Biological and Environmental Sciences, P.O. Box 35, 40014 University of Jyväskylä, Finland.
e-mail: eric.letortorec@jyu.fi

Adriano Mazziotta is a post-doctoral researcher at the Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden.
Address: Stockholm Resilience Centre, Stockholm University, Kräftriket 2b, 11429 Stockholm, Sweden.
e-mail: adriano.mazziotta@su.se

Tord Snäll is a Professor of Ecology at the Swedish University of Agricultural Sciences, Uppsala, Sweden.
Address: Swedish Species Information Centre, Swedish University of Agricultural Sciences (SLU), PO 7007, 750 07 Uppsala, Sweden.
e-mail: tord.snall@slu.se

Mikko Mönkkönen is Professor of Ecology and Environmental Management at the Department of Biological and Environmental Sciences, the University of Jyväskylä, Finland.
Address: University of Jyväskylä, Department of Biological and Environmental Sciences, P.O. Box 35, 40014 University of Jyväskylä, Finland.
e-mail: mikko.monkkonen@jyu.fi