# Chapter 25
# Modeling the Impacts of Climate Change on Ecosystem Services in Boreal Forests

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**Abstract** With the increasing effects of climate change, a rapid development of effective approaches and tools are needed to maintain forest biodiversity and ecosystem functions. The response, or lack thereof, of forest managers to climate change and its impacts on ecosystem services will have broad ramifications. Here we give an overview of approaches used to predict impacts of climate change and management scenarios for a range of ecosystem services provided by the boreal forest, including timber supply, carbon sequestration, bioenergy provision, and habitat for wildlife and biodiversity. We provide examples of research in the field and summarize the outstanding challenges.

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## 25.1 Introduction

Climate change and intensive forestry are important drivers of altered forest dynamics and related changes in the provision of ecosystem services in boreal forests. As defined by the Millennium Ecosystem Assessment (2005),

> Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as regulation of floods, drought, land degradation, and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious, and other nonmaterial benefits.

Boreal forests provide a large variety of ecosystem services. These include timber, food, bioenergy, carbon sequestration, habitat for wildlife, water regulation, as well as recreational, spiritual, and religious experiences (Fig. 25.1; Shvidenko et al., 2005). As discussed in the earlier chapters of this book, climate change will not only affect the distribution of tree species but will likely affect disturbances, such as the frequency of forest fires, the importance of windthrow, and the severity of insect infestations (Chaps. 3 and 4). These effects will, in turn, disrupt ecosystem services provided by the forest. Much evidence exists that the boreal forest has already responded to climatic changes. Soja et al. (2007) reviewed observed shifts in tree line in Siberia, decreased growth of white spruce (*Picea glauca*), increases in extreme fire years in Siberia, Alaska, and Canada, and multiyear outbreaks of the spruce beetle (*Dendroctonus rufipennis*) in Alaska. Since this review, much more evidence has emerged (see Brecka et al., 2018). Outbreaks of mountain pine beetle (*Dendroctonus ponderosae*) have occurred in large parts of Canada since the 1990s, affecting more than 18 million ha of forest (NRC, 2020). Extreme fire events and severe outbreaks of insect pests that alter entire ecosystems are expected to become even more common in the future (Safranyik et al., 2010; Stocks et al., 1998; Wolken et al., 2011). Trees will therefore experience increased stress levels (Rebetez & Dobbertin, 2004; Schlyter et al., 2006), likely enhancing their sensitivity to damage (Schlyter et al., 2006). Such events can have devastating impacts on forest ecosystem services through tree mortality and subsequent economic losses, reduced wildlife habitat, and decreased carbon storage capacity (Chan-McLeod, 2006; Kurz et al., 2008; Nealis & Peter, 2008).

Although the risk of natural disturbances in forests may increase, management practices will alter the extent of the damage (Schlyter et al., 2006). The effect of these changes is likely to have significant consequences for, among others, the forestry sector. There is, therefore, an increasing awareness of the necessity to adapt forest management practices to mitigate the adverse effects of climate change (Keenan, 2015) through increasing the uptake of carbon by vegetation (Lindenmayer et al., 2012) and reducing storm- and insect-related tree damage (Felton et al., 2016; Imai et al., 2009). However, the particular choice of management strategy to use in forest ecosystems will have marked consequences on the responses of forest ecosystems and, therefore, the range of ecosystem services provided by forests (Imai et al., 2009; Schlyter et al., 2006). A solid understanding of how climate change will affect forest

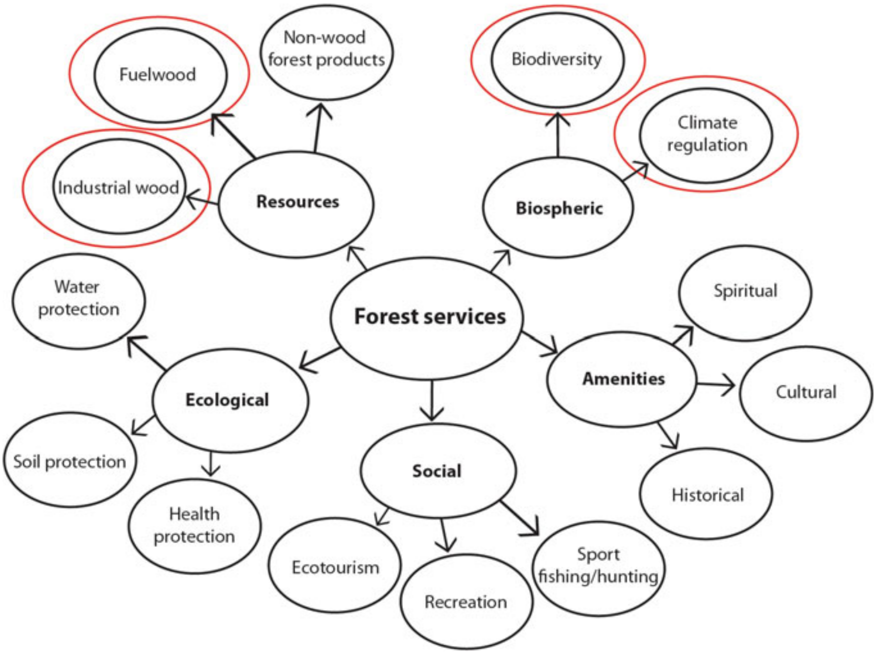



**Fig. 25.1** Major classes of forestry services as defined by Shvidenko et al. (2005), including the ecosystem services discussed in this chapter (*red circles*). Modified from Fig. 21.6 in Shvidenko et al. (2005). *Chapter 21 Forest and woodland systems. Ecosystems and Human Well-Being: Current States & Trends* by the Millennium Ecosystem Assessment. Copyright © 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, DC

dynamics is therefore required if we want to safeguard the ecosystem services offered by boreal forests.

Forest landscape models and decision-support systems can assess the effects of future climate change, shifts in disturbances and management practices, and the establishment of new floral and faunal species within boreal forest ecosystems (Borges et al., 2014). The extensive range of relevant economic, ecological, and social aspects incorporated within long-term forest management planning can be overwhelming for decision-makers; therefore, multiple forest landscape models and forest decision-support systems have been developed globally over the last decades (Borges et al., 2014; Xi et al., 2009). A forest landscape model simulates the survival, growth, and mortality of trees (or stands of trees) over time at relatively large spatial scales (He, 2008). There are many different forest landscape models. In the 1970s, forest gap models were developed to simulate the within-site survival, growth, and mortality of individual trees. An example of such a model is JABOWA (Botkin et al., 1972). A couple of decades later, gap models were developed to assess the (long-term) impacts of climate change on forests; examples of such models include LINKAGES (Post & Pastor, 1996) and ZELIG (Miller & Urban, 1999). Since the early 1990s, many forest landscape models have been developed to simulate forest ecosystems at larger scales. These models include LANDIS (He et al., 1999), which then served as the basis for other, more recent models, such as LANDIS-II (Scheller et al., 2007) and FIN-LANDIS (Pennanen & Kuuluvainen, 2002). Moreover, many extensions able to be coupled to these models have been built to simulate additional processes, such as the impacts on carbon pools (Forest Carbon Succession Extension v.2.0 ForCS, Dymond et al., 2016) and impacts of ungulate browsing (Browsing extension, De Jager et al., 2017). Xi et al. (2009) provide an overview of many of the earlier forest landscape models.

A decision-support system is a model-based software system that combines a knowledge system consisting of forest data, models (e.g., a forest landscape model that simulates tree survival, growth, and mortality), and methods (e.g., statistical computations or optimization solvers) with a problem-processing system to calculate the outcome of management scenarios. The entire decision process becomes reproducible and rational through this decision-support system. An example is the Swedish Heureka program, which can handle simulations of forest management practices, timber production, carbon sequestration, bioenergy, biodiversity, recreation, and economic values (Wikström et al., 2011). Orazio et al. (2017) provide an overview of many decision-support systems used in Europe. Nordström et al. (2019) reviewed the capacity of nine European forest decision-support systems to cope with impacts of climate change for a variety of ecosystem services.

The required information for forest landscape models and forest decision-support systems generally includes detailed information on the initial conditions of the study site (e.g., biomass and age composition of the dominant tree species) as well as such parameters as tree species' longevity, seed dispersal, shade and fire tolerance, vegetative reproduction probability, minimum sprout age, and growth rates. Furthermore, detailed information regarding the environmental conditions, such as precipitation, temperature regimes, and soil properties, are often required. Additional information may be sought, depending on the study aims. Such information generally requires the availability of detailed forest survey data or extensive fieldwork, and a lack of this vital information can therefore hamper the reliability of outcomes.

Multiple studies have relied on forest landscape models or decision-support systems to evaluate the consequences of forestry practices on ecosystem services, as it is generally not possible to examine the various effects of different management strategies on the forest using field studies. Such studies are generally focused on stemwood production rather than other ecosystem services, such as bioenergy harvesting or the provision of wildlife habitat (Biber et al., 2015; Eyvindson et al., 2018; Garcia-Gonzalo et al., 2015). These studies do, however, provide valuable information on, for example, possibilities for increased carbon sequestration (Lucash et al., 2017), optimal restoration practices for forests having sustained damage (Xi et al., 2008), and wildlife preservation (Hof & Hjältén, 2018). They can thus be used to identify *best practice* management strategies to safeguard high levels of several ecosystem services. In this chapter, we provide an overview of the current status and examples of studies that use forest landscape models or decision-support systems to assess the impacts of climate change and management scenarios on several of the most commonly studied ecosystem services provided by the boreal forest: timber supply,

**Fig. 25.2** Timber transport on the Northern Dvina River in Arkhangelsk, Russian Federation, June 2010. *Photo credit* Anouschka Hof

carbon sequestration, bioenergy provision, and wildlife habitat. We then discuss some current challenges (Fig. 25.2).

## 25.2 Timber Production

The past few decades have shown that climate change will likely have a large impact on timber production in boreal forests. These impacts will vary according to geographic location, the dominant tree species, insect and disease outbreaks, and management strategies. The growth rates of boreal forests are limited mainly by short growing seasons. Assuming adequate water supplies, increased temperatures (and carbon dioxide fertilization) may enhance growth and timber volume. However, a more prolonged and enhanced growing season alone does not explain all the uncertainty in projections of future boreal forests. Indeed, changing temperature and precipitation regimes may have both positive and negative effects on future tree growth; for example, summer temperatures may heighten tree respiration that will result in reduced growth. Alternatively, growth may be enhanced if summer respiration demands are offset by a longer growing season (because of an earlier spring, longer autumn, or both). The effects on timber production are therefore uncertain.

Goldblum and Rigg (2005) found, for instance, that whereas commercially valuable sugar maple (*Acer saccharum*) was predicted to experience an increase in its growth rate in the deciduous–boreal forest study site in Ontario, Canada, balsam fir (*Abies balsamea*), another commercially valuable species, was likely to experience decreased growth rates. Uncertainties related to how climate will change compound this challenge of projecting the future growth of boreal taxa.

Ultimately, the most significant impacts of climate change on future timber supply in the boreal forest may be linked to indirect effects, such as insect outbreaks (Safranyik et al., 2010). For example, invasive insects (either currently known or unknown from the boreal region) may increase drastically under a warmer climate to cause the widespread mortality of a commercially valuable species. This event could then lead to extensive salvage harvesting of dead and dying individuals of these tree species and overwhelm timber markets. The hemlock woolly adelgid (*Adelges tsugae*), currently kept in check by cold winters, offers an example of an insect pest found south of the boreal forest in North America that is moving northward because of climate warming and causing the large-scale mortality of eastern hemlock (*Tsuga canadensis*). As another possible scenario, land-use changes driven by economics related to global climate change may cause landowners in the boreal forest to abandon current silvicultural systems for other land uses or ecosystem services, such as land development, agriculture, carbon sequestration, and water protection.

The need to understand the interacting effects of climate change with insects, timber markets, land use, and other disturbances on the timber supply of boreal forests makes forest decision-support systems and landscape models able to incorporate multiple interacting drivers well poised to explore multiple scenarios and tease apart these drivers. In addition to the general tree species' parameters and the environmental conditions needed to run such models, parameters related to, for example, merchantable age, market prices, and management strategies are commonly required. Over the next decade, we expect much research in this area to help explore the uncertainty in future boreal forest timber supply. Multiple interacting effects currently lead to much uncertainty in regard to the outcomes, and current modeling efforts are just beginning to address these numerous interactions (Duveneck & Scheller, 2016; Dymond et al., 2014; Hof et al., 2021; Orazio et al., 2017).

Meanwhile, the call to use alternative management strategies is increasing. Specific adaptive management strategies have been proposed, including those of Spittlehouse and Stewart (2003) and Millar et al. (2007). These strategies include (1) shorter rotation times to decrease the period of stand vulnerability or facilitate a shift to more climate-suitable species; (2) assisted migration of tree species or provenances in anticipation of future losses of productivity with existing species/varieties; (3) tree species diversification strategies aimed at increasing forest resilience; and (4) conservation of corridors to facilitate species migration. However, similar to the direct effects of climate change, such strategies may have large impacts on timber production and other ecosystems services (Felton et al., 2016; Lindenmayer et al., 2012; Noss, 2001). Robust predictions for a range of scenarios are therefore required. Multiple examples of such studies exist, particularly from Canada and Finland, whereby researchers have attempted to predict forest landscape response to climate change and various management strategies, including those proposed above, using various forest decision-support systems and landscape models.

Brecka et al. (2018) reviewed the impacts of climate change on ecological processes in established boreal forest stands and the effects on timber supply and forestry. They found that climate change has led to a reduced rate of volume accumulation and, thus, less timber available for harvest (Fig. 25.3). Their review suggests that climate change, although spatially variable, has already produced significant adverse effects on the timber supply in the boreal forest. Although not necessarily expected, Brecka et al. (2018) found that climate change favored pioneer species, such as pine (*Pinus* spp.) and poplar (*Populus s*pp.), over late-successional species, such as spruce (*Picea* spp.) and fir (*Abies* spp.). Climate-suitable species may have been correlated with shade tolerance, thus affecting successional dynamics at the stand level. Ultimately, the boreal forest industry may need to adapt silviculture systems to incorporate and find markets for climate-adapted species. Incorporating alternative tree species more suited to future climate regimes has been proposed (Millar et al., 2007) and simulated as an alternative climate change adaptation strategy by several studies focused on Siberia (e.g., Nadezda et al., 2006) and North America (e.g., Duveneck & Scheller, 2016; Hof et al., 2017).

In Fennoscandia, almost all forested land is managed, and the boreal forest is dominated mainly by Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and to a smaller extent by birch species (*Betula* spp.). All these species are heavily exploited for producing sawtimber and wood pulp (Esseen et al., 1992). With changing climatic conditions, tree species composition is expected to change under baseline forest management strategies, with birch and Scots pine increasing at the expense of Norway spruce. At the same time, future timber production is expected to increase significantly because of the longer growing seasons, thereby increasing growing stock

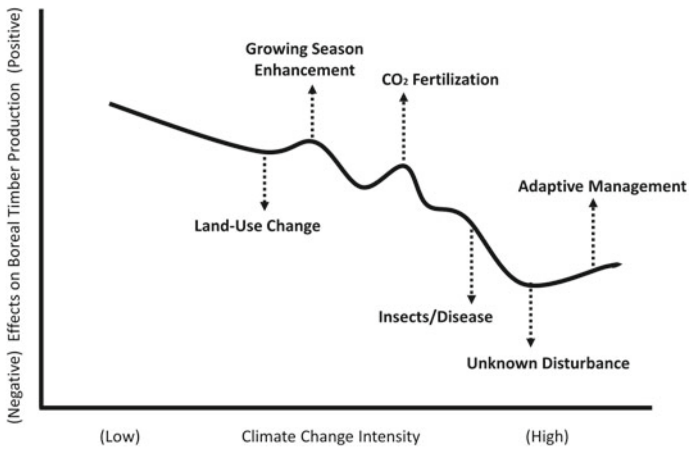



**Fig. 25.3** Theoretical interacting effects of climate change and disturbances on boreal timber supply. Indirect effects of climate change (*dotted lines*) may have positive or negative effects on timber supply. These effects will vary depending on climate change intensity

(Peltola et al., 2010). Garcia-Gonzalo et al. (2007) assessed the impacts of climate change and management practices on the timber yield of a 1,450 ha forest management unit in Finland dominated by Scots pine, Norway spruce, and silver birch (*Betula pendula*); they estimated an enhanced growth of 22% to 26% resulting in a 12% to 13% increase in timber yield. The greatest yields were obtained when a thinning regime with high stocking was used with a 100-year rotation period. Subramanian (2016) showed that changing the thinning regime, shortening rotation periods, and planting hybrid tree species such as hybrid aspen (*Populus tremula* × *P. tremuloides*) and hybrid larch (*Larix* × *Eurolepis*) could increase future timber yields. In northern Minnesota, at the boreal-temperate forest ecotone, Duveneck and Scheller (2016) used LANDIS-II coupled to the Biomass-Succession extension and found that climate change had a negative effect on simulated aboveground and harvested biomass. They explored multiple alternative silviculture systems, including expanding reserve areas and changing rotation lengths. However, the climate-suitable planting of broadleaf species currently found immediately south of the studied landscape resulted in the greatest increase in harvested and aboveground biomass. In a Finnish study using the simulation–optimization software Monsu (Pukkala, 2004), Díaz-Yáñez et al. (2020) simulated five separate management scenarios under climate change and found that silviculture systems that used thinning from above were profitable and provided more additional ecosystem services. However, as outlined here, future modeling work will continue to address multiple interacting effects of climate change on boreal forest timber supply and other ecosystem services (Fig. 25.4; Hof et al., 2021).

## 25.3 Carbon Sequestration

Boreal forests, encompassing approximately 30% of the forested area across the globe (Brandt et al., 2013), may play a pivotal role in halting or slowing climate change by sequestering carbon (Melillo et al., 1993). As about two-thirds of the boreal forest is under some form of management, its current and future resilience and ability to store carbon depend mainly on which management strategies are chosen (Gauthier et al., 2015) and the severity and frequency of natural disturbances. Although forest ecosystems are often carbon sinks, natural disturbances such as large insect outbreaks, e.g., that are currently occurring in Canada, can change a forest ecosystem from a carbon sink into a source (Kurz et al., 2008). Altered fire regimes may also have large impacts on boreal carbon stocks (Miquelajauregui et al., 2019a). As potential disturbances, such as insect outbreaks and wildfires, are expected to become increasingly frequent with future climate change (Safranyik et al., 2010; Stocks et al., 1998; Wolken et al., 2011), it is crucial to have a good understanding of carbon cycles in forest ecosystems. Forest managers and other stakeholders are becoming increasingly aware that alternative management practices may need to be applied in forest ecosystems to increase carbon uptake by vegetation (Ameray et al., 2021; Fares et al., 2015) or reduce emissions caused by natural disturbances (Noss, 2001). However, different

**Fig. 25.4** Harvested trees, northern Minnesota, USA. The availability of future timber supply from boreal forests will depend on many interacting factors. *Photo credit* Matthew Duveneck

management practices can have different consequences for the ability of forests to sequester carbon; forest management can increase or reduce sinks and emissions (Kurz et al., 2008). Furthermore, as mentioned in the previous section, climate change effects on growth rates remain uncertain and may increase or decrease the capacity of forests to store carbon.

As it is difficult to assess the impacts of all these environmental changes on the capacity of boreal forests to sequester carbon in field studies at large scales, several studies have aimed to predict such impacts using forest landscape models or decision-support systems. In addition to the general parameters mentioned in Sect. 25.1, such models generally require parameters on deadwood matter and tree species decay rates under various conditions.

Several modeling studies have investigated boreal carbon storage under future scenarios for European and Asian forests. Ito (2005) developed a coupled carbon cycle and fire regime model for the larch (*Larix gmelinii* and *Larix cajanderi*)-dominated boreal forest of eastern Siberia and found that fire events, which are expected to become more frequent in the future (Stocks et al., 1998; Wolken et al., 2011), released approximately 12% of the carbon fixed by the vegetation and lead to an accelerated carbon cycling in the forest. Gustafson et al. (2011) used LANDIS-II coupled with Biomass-Succession to predict the effects of climate change in another region in Siberia. They assessed climate impacts on timber harvesting and insect outbreaks on a Scots pine–dominated boreal forest landscape in the Chuno-Angarsky region. They predicted direct effects of climate change on the forest ecosystem and modeled that changes to the forest's ability to hold carbon would be relatively minor compared with the effects of (novel) forest management practices and the increased risk of insect pest outbreaks. Jiang et al. (2002) used the ecosystem process model CENTURY 4.0 to assess the impact of various harvest disturbance regimes on the carbon stocks and fluxes of a boreal forest landscape in China. They concluded that carbon stocks in their landscape could markedly increase under harvests at 100- to 200-year rotations. The FINNFOR model when applied to implemented thinning regimes in Finland, which allow a higher stocking of trees relative to current practices in the managed boreal forest, indicated that this approach would increase the amount of carbon in the forest ecosystem by up to 11% and the timber yield by up to 14%, depending on the climate trajectory (Garcia-Gonzalo et al., 2007). Therefore, this modeling suggests that carbon sequestration in boreal forest ecosystems may be enhanced using certain management regimes without loss of timber production, even with future climate change. The land ecosystem model JSBACH and the stand growth model PREBAS assessed the impacts of current management practices in Finland and future climate change on ecosystem services provided by the boreal forest; the models indicated a potential increase in the annual carbon sink of approximately 40% at the end of the twenty-first century because of increased annual forest growth (Holmberg et al., 2019).

Examples of modeling boreal forest response to climate change in North America include that of Lucash et al. (2017). They used LANDIS-II coupled with the Century Succession extension to simulate the capacity of various forest management strategies to maintain or increase forest landscape resilience along the broadleaf–boreal transition zone in north-central Minnesota over the next century. They found that climate change would lower forest resilience and that a scenario aimed at maximizing carbon storage by harvesting 30% less land and increasing rotation length did not perform better than their business-as-usual scenario. Forest resilience did increase through use of adapted management strategies and the planting of species adapted to expected future conditions. In the same forest landscape, Lucash et al. (2018) then simulated the effects of fire, insect, wind, and forest management disturbances under changing climatic conditions on this forest. They found that whereas changing climate was the most important driver of soil carbon—leading to smaller future stocks because of increased heterotrophic respiration—simulated future disturbance regimes affected aboveground carbon stocks to a greater extent. In Canada, Miquelajauregui et al. (2019b) simulated the response of carbon stocks to climate change in a black spruce (*Picea mariana*)–dominated landscape in northern Québec. They used an R software–based simulation model having three interacting modules: patch, fire, and carbon dynamics. Their simulations showed that climate change reduces carbon storage by 10% by the end of 2100.

Results across the boreal forest biome suggest that whereas the capacity of boreal forests to store carbon may increase as a result of greater annual forest growth related to a changing climate, increases in natural disturbances, i.e., fire and pest outbreaks, and the potential augmentation in harvest rates may have significant effects on boreal forest carbon stocks; thus, much of the boreal forest may instead act as a carbon source. The increased uncertainty in regard to the direction, severity, and frequency of a multitude of natural and anthropogenic disturbances and their effect on the capacity of forests to sequester carbon under future warming both heighten the complexity of decision-making for forest managers when selecting and implementing management strategies. Several studies from across the boreal region (as well as other regions) suggest that management strategies aimed at increasing species diversity and resilience may effectively reduce the risks of increased greenhouse gas emissions (Fig. 25.5; Duveneck & Scheller, 2016; Dymond et al., 2014; Hof et al., 2017).

Management strategies aimed at increasing species diversity and resilience may not be sufficient, however, to fully offset the impacts of climate change and natural disturbances and should be tailored to the individual ecosystems to be most effective. Ontl et al. (2020) developed a Forest Carbon Management Menu to help managers identify forest adaptation strategies beneficial for storing forest carbon by reducing climate change–related losses of carbon, sustaining forest health, and enhancing productivity. In addition to simulations of how landscapes may respond to climate change, such tools can guide decision-makers and help mitigate climate change by increasing carbon stocks in the boreal forest through the appropriate selection of forest management strategies.

**Fig. 25.5** An increase in species diversity may help boreal forests respond to climate change. Photo of the boreal–deciduous transition zone, northern Minnesota. *Photo credit* Matthew Duveneck

## 25.4 Bioenergy

From the moment humans discovered fire, our species began using biomass for energy; however, bioenergy has gained increasing attention as a more climate-neutral energy source relative to fossil fuels in recent years. The share of bioenergy, defined as renewable energy from biological sources, is expected to increase and contribute to mitigating climate change (IPCC 2014; Creutzig et al., 2015). However, there are uncertainties, and several factors affect whether bioenergy use helps or hinders climate change mitigation.

The assumption that bioenergy is carbon neutral is based on biogenic $CO_2$ emissions from the use of harvested biomass eventually being absorbed by biomass regrowth through photosynthesis (Ragauskas et al., 2006). If proper management is adopted, there is a possibility to ensure that the harvesting and use of bioenergy are carbon negative (Lehmann, 2007). Nonetheless, carbon loss from forests used for bioenergy is distinctly possible, contradicting its effectiveness in mitigating climate change. The mitigation role of forest bioenergy thus depends on case-specific factors, such as the biophysical features of the biomass production system and the greenhouse gas intensity of the energy source that bioenergy replaces (Cowie et al., 2019). Moreover, time is an important aspect. Harvesting biomass for bioenergy decreases the forest carbon stock—compared with not harvesting for bioenergy. This decrease balances out over time by lowering greenhouse gas production by replacing fossil fuels. Until this point in time, however, more $CO_2$ is released from the bioenergy-based system than the fossil fuel system. The length of this carbon payback time varies and depends on many factors, including forest characteristics, the type of biomass used, the fossil fuel being replaced, and alternative land use; for the boreal forest, this payback is likely over several decades (Agostini et al., 2014).

Despite the uncertainties related to the effect of bioenergy on climate, harvesting for bioenergy is expected to increase in the future. As the current outtake is far less than its potential because of low demand, increasing prices for biomass feedstock will substantially increase the outtake. Woody biomass used for energy can be from primary sources available after harvesting operations, such as branches and treetops as well as stumps and stems, all produced from operations focused on harvesting biomass during early thinning or stems that are downgraded from other assortments (Fig. 25.6). Secondary sources include industrial by-products, such as bark, sawdust, and shavings, that accumulate during processing operations. Finally, a third source, including end-of-life wood products, such as construction and demolition wood, are also usable for energy. Extraction of woody biomass has consisted mainly of logging residues; however, the share of stumps and roundwood is most likely to increase with a greater demand (Díaz-Yáñez et al., 2013).

Since forestry has such large impacts on other ecosystem services, adding residue extraction has only a minimal additional effect (de Jong & Dahlberg, 2017). Deadwood-dependent species are adversely affected, whereas the effect on other species is not as uniform; some are impacted positively, others negatively. Although most ecosystem services are adversely affected by residue extraction (e.g., soil

**Fig. 25.6** Conventional forwarder loaded with small-diameter trees from a bioenergy thinning operation in Bräcke, northwestern Sweden, October 2019. *Photo credit* Raul Fernandez Lacruz

quality, productivity, and water quality), for recreation and pest–fungi control the relationship can be the opposite (Ranius et al., 2018).

Most studies investigating the consequences of bioenergy harvesting have focused on stand-scale and short-term impacts (Ranius et al., 2018). The boreal forest management system is slow, with rotation times of up to almost 100 years. Evaluating the long-term consequences of harvesting for bioenergy on other ecosystem services and any future potential for biomass harvest relies on simulations with forest landscape models or forest decision-support systems (Borges et al., 2014). Additional parameters beyond the general tree-species-specific parameters and environmental conditions include biomass pools of all parts of the tree, e.g., branches, foliage, and bark. Examples of using such a model or system to evaluate consequences from bioenergy extraction include that of Repo et al. (2020). They applied the SIMO modeling framework, complemented with Yasso07 for soil carbon modeling, to simulate forest development over 100 years in Finland, both with and without residue extraction. They concluded that biodiversity, especially deadwood-associated species, is threatened by residue harvest. They also showed that the forest carbon balance is affected. The emission savings from bioenergy is reduced because of lower carbon stocks when harvesting residues, especially during the first decade post-extraction, supporting the carbon payback-time assumption. Furthermore, they conclude that stands having a high biodiversity potential also often have a high potential for producing bioenergy, which complicates the trade-off between management strategies.

In a study in central Sweden, Hof et al. (2018) used LANDIS-II coupled with the Forest Carbon Succession Extension to simulate the effects of various bioenergy extraction scenarios on deadwood availability and the subsequent habitat suitability for saproxylic species. They found that—in their landscape already largely depleted of deadwood—even a scenario aimed at species conservation only led to about 10 $m^3$ deadwood per ha, a low value relative to deadwood volumes in many other parts of the boreal region. In a study in northern Sweden, Eggers et al. (2020) evaluated an intensive bioenergy harvest strategy, also using small-diameter trees in early thinning, and compared this approach with the prevailing strategy where only residues (tops and branches) are harvested. The simulations, using Heureka and covering 100 years, found a considerable potential to increase bioenergy harvest with the more intensive strategy, without substantial adverse effects on biodiversity and carbon storage. There was also room for a simultaneous increase in harvest residue extraction, improved conditions for biodiversity, and increased carbon stocks relative to current levels; however, this scenario requires effective forest management planning that considers all critical aspects.

## 25.5 Wildlife Habitat and Biodiversity

In addition to the direct impacts of climate change on species inhabiting forest ecosystems, forest management adaptations may affect the wildlife inhabiting boreal forests. These effects may be negative (Lindenmayer et al., 2012; Noss, 2001) or positive (Imai et al., 2009), and under current forest management practices, national environmental objectives to conserve wildlife are not being attained (e.g., Swedish Environmental Protection Agency, 2022). Thus far, scenario-based assessments of the impacts of climate change adaptation strategies on forests have mainly targeted ecosystem services limited to carbon uptake and forest productivity, ignoring wildlife. A likely reason for this exclusion is that forest landscape models and decision-support systems used for scenario-based assessments were initially developed to investigate the impacts on timber and pulp production (Borges et al., 2014; Xi et al., 2009). Studies investigating the effects of climate change on forest wildlife frequently ignore the indirect impacts that climate change may have on the various ecological processes within forest landscapes (Keenan, 2015). Instead, modeling efforts often rely on species distribution models and decision trees or focus on the population viability of targeted species on the basis of their known suitability to various environmental conditions. Therefore, such studies ignore the impacts of climate change and forest management strategies on important ecological processes affecting forest dynamics.

The modeling community has recently started to integrate wildlife models into forest landscape models and decision-support systems to conduct scenario-based assessments of wildlife response to climate change adaptation strategies in forests (e.g., He, 2009; Kolström & Lumatjärvi, 1999). The required parameters for such an exercise, in addition to the general tree-species-specific parameters and environmental conditions, are heavily dependent on those wildlife species on which studies have focused. Deadwood-related parameters are needed when studying the effects of climate change and forest management on saproxylic species, and data on understory vegetation is required for modeling climate impacts involving browsers. Several efforts have used landscape models to infer habitat suitability for wildlife in the boreal forest. For instance, Tremblay et al. (2018) projected the cumulative impacts of climate change and forest management strategies in the boreal forest of eastern Canada on the Black-backed Woodpecker (*Picoides arcticus*). They simulated forest attributes relevant to this woodpecker using LANDIS-II and PICUS to infer future landscape suitability for the species under various climate change scenarios. Tremblay et al. (2018) found that such cumulative impacts produced significant adverse effects on the woodpecker and on the biodiversity associated with deadwood and old-growth boreal forests. To help mitigate these negative impacts, they suggested adaptations to current management practices, including reduced harvesting levels and strategies to promote coniferous species. Pearman-Gillman et al. (2020) used the land change model Dinamica EGO and several future forest scenarios—developed using LANDIS-II in combination with species distribution models—to assess how species distributions for nine mammal and one bird species changed under five trajectories of modified landscapes in New England in the northeastern United States. They predicted that seven of these species would experience regional declines irrespective of the landscape change trajectory. A similar approach was used by Hof and Hjältén (2018) in Sweden. They also used LANDIS-II coupled with Biomass-Succession to simulate the effects of different levels of restoration on a boreal forest landscape in central Sweden and inferred the landscape suitability for the White-backed Woodpecker (*Dendrocopos leucotos*); an umbrella species in the boreal forest of Fennoscandia; its protection may serve to preserve a range of species that favor high amounts of deadwood and old-growth forest (Fig. 25.7). This study, however, did not incorporate the possible impacts of future climate change. De Jager et al. (2020) also used LANDIS-II coupled with Biomass-Succession and the PnET-II ecophysiology model to simulate how climate change and different wolf (*Canis lupus*) management intensities would affect moose (*Alces alces*) densities and the subsequent impacts on the forests of Isle Royale National Park, Michigan, United States. They found that irrespective of predation pressure, browsing by moose under projected changes in climate leads to strong declines in total forest biomass. Lagergren and Jönsson (2017) used the biogeochemical ecosystem model LPJ-GUESS to study the impact of climate change and alternative management strategies on timber production, carbon storage, and biodiversity in one nemoral and two boreal forest landscapes in Sweden. Their simulations, using the fraction of broadleaf forest, the proportion of old trees, the proportion of old broadleaf trees, and stem litter as proxies for biodiversity, demonstrated that increasing the proportion of broadleaf trees, associated with increasing levels of biodiversity, can promote the storm resistance of a forest landscape.

**Fig. 25.7** Forest restoration in the boreal forest landscape in Sweden simulated by Hof and Hjältén (2018)—eliminating coniferous trees and creating deadwood to benefit the White-backed Woodpecker in Sweden. *Photo credit* Anouschka Hof

Several forest management practices have thus far been applied with the aim of mitigating climate change and simultaneously increasing biodiversity in forests. Whereas the study by Tremblay et al. (2018) in Canada advocated strategies to promote coniferous species to benefit the Black-backed Woodpecker, strategies to promote broadleaf species to benefit the White-backed Woodpecker (Hof & Hjältén, 2018) and biodiversity in general (Lagergren & Jönsson, 2017) were suggested for Sweden. Both strategies would, however, lead to a more diverse forest in their respective settings, and the diversification of forests is commonly cited as a climate change mitigation strategy and a means to generate the highest possible levels of various ecosystem services, including habitat provision for wildlife (Lagergren & Jönsson, 2017; van der Plas et al., 2016).

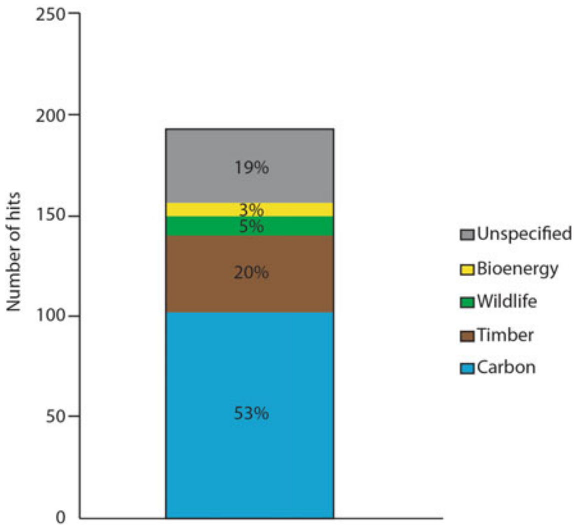
Other climate change mitigation strategies that could benefit biodiversity include thinning practices. Thinning practices can promote high carbon sequestration rates and enhance the structural and compositional complexity in forests (D'Amato et al., 2011), both of which may be good indicators of high forest biodiversity (Lindenmayer et al., 2000). Uneven instead of even-aged management and prescribed fire regimes have also been proposed as mitigation measures to benefit biodiversity (Millar et al., 2007). Moreover, tree retention practices are frequently used to alleviate the adverse effects of felling on species (Gustafsson et al., 2010). Such measures are commonly introduced to promote structural complexity, forest continuity, and the availability of deadwood and old-growth forest patches, which are all generally related to high levels of species diversity (Paillet et al., 2010). A literature review by Felton et al. (2016) assessed the implications for biodiversity of several climate change adaptation and mitigation strategies implemented in Swedish production forests. They concluded that forest managers will be obliged to accept trade-offs to implement climate change adaptation strategies and meet the biodiversity goals set by the Swedish government. This scenario is likely to hold for other boreal countries as well.

## 25.6 Outlook and Challenges

Predictions of climate change impacts on the provision of boreal ecosystem services face several major challenges. These include uncertainties surrounding the potential distribution and productivity of future boreal forests related to uncertainties in the projections of future climate (Hof et al., 2021; Keenan, 2015; Prestele et al., 2016). Such uncertainties complicate decisions and developments regarding (novel) adaptation and mitigation strategies for managing the forest. Trade-off analyses and multiobjective optimization techniques can evaluate the consequences of conflicting management strategies on multiple ecosystem services (Chen et al., 2016). Tools such as decision-support systems may play a role in performing optimization across multiple objectives; however, to our knowledge, no system currently exists that incorporates the multitude of ecosystem services provided by the boreal forest. Furthermore, the numerous existing models and decision-support systems are very data hungry. It is questionable whether high-quality data are available throughout the boreal forest biome for all required parameters. Much time and effort are likely needed to collect the essential data to set up reliable models and support systems. However, once set up, they should be able to guide decision-makers in selecting appropriate management strategies. Data obtained via remote sensing, such as through LiDAR, MODIS, and Landsat, may play prominent roles in the future in regions where field data are not readily available.

Screening the published literature, we find that most studies focus on boreal forest landscapes in Europe and northern North America. As more than half of all boreal forests occur in the Russian Federation, producing about 20% of the world's timber resources (Krankina et al., 1997), it is paramount that we have a good understanding of how climate change may affect boreal forests and the associated ecosystem services in this region. However, studies related to the boreal forest in the Russian Federation and published in the peer-reviewed literature in English are severely lacking. Furthermore, a quick search in Web of Science illustrates that the primary focus of the research community (to the present) in regard to studies of climate change impacts on ecosystem services provided by boreal forests is mainly on carbon sequestration. We found 53% of the hits addressed carbon, 20% timber, and 5% wildlife. Few studies focused on bioenergy provisions in the context of boreal forests facing climate change (3%, Fig. 25.8). Harvesting for bioenergy appears less developed in Siberia

**Fig. 25.8** Number of hits in May 2020 for the search string "Topic: boreal forest AND climate change AND ecosystem services" refined by "carbon," "timber," "wildlife," and "bioenergy" in Web of Science




and North America than in Fennoscandia, as inferred by the number of studies in the published English-language literature from Sweden and Finland in regard to this particular ecosystem service.

Here we have overviewed the complexities and uncertainties of the boreal forest under climate change. It is clear that interacting, indirect effects of climate change on the boreal forest will be significant, which has a large impact on simulation outcomes (Lucash et al., 2018). Future modeling studies will undoubtedly need to address these compounding effects. Massive challenges lie ahead for forest managers to safeguard boreal ecosystem services while also maintaining ecosystem resilience. Fortunately, multiple tools exist to aid their decision-making. Furthermore, frameworks to incorporate uncertainty within forest management facing the additional challenge of climate change have been developed (Daniel et al., 2017) and provide additional guidance to forest managers.

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