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REVIEW

Enhancing Resilience of Boreal Forests Through Management Under Global Change: a Review

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Abstract

Purpose of Review Boreal forests provide a wide range of ecosystem services that are important to society. The boreal biome is experiencing the highest rates of warming on the planet and increasing demand for forest products. Here, we review how changes in climate and its associated extreme events (e.g., windstorms) are putting at risk the capacity of these forests to continue providing ecosystem services. We further analyze the role of forest management to increase forest resilience to the combined effects of climate change and extreme events.

Recent Findings Enhancing forest resilience recently gained a lot of interest from theoretical perspective. Yet, it remains unclear how to translate the theoretical knowledge into practice and how to operationalize boreal forest management to maintain forest ecosystem services and functions under changing global conditions. We identify and summarize the main management approaches (natural disturbance emulation, landscape functional zoning, functional complex network, and climate-smart forestry) that can promote forest resilience.

Summary We review the concept of resilience in forest sciences, how extreme events may put boreal forests at risk, and how management can alleviate or promote such risks. We found that the combined effects of increased temperatures and extreme events are having negative impacts on forests. Then, we discuss how the main management approaches could enhance forest resilience and multifunctionality (simultaneous provision of high levels of multiple ecosystem services and species habitats). Finally, we identify the complementary strengths of individual approaches and report challenges on how to implement them in practice.

Keywords Adaptive management · Biodiversity · Ecological modeling · Forest management · Silviculture · Socio-economic conditions

Introduction

Boreal forests, representing approximately one-third of the remaining global forests [1] (Fig. 1), provide a wide range of ecosystem services that are important to human well-being [2]. Among the most relevant services are timber production (boreal forests constitute approximately 45% of the world's stock of growing timber) [3], climate change mitigation (they store about one-third of the global terrestrial carbon) [4], regulation of water, soil and air quality, non-wood forest products (e.g., wild berries, mushrooms, and game), and recreation opportunities [5, 6]. Boreal forests also play a key role for biodiversity conservation as they provide critical habitats for many species [2]. Such multifunctionality, i.e., simultaneous provision of high levels of multiple ecosystem services and species habitat, is often conflicting with intensive exploitation of timber in boreal forest landscapes (e.g., [7]).

While deforestation is not a major concern in the boreal forest biome, roughly half of its area has been subjected to human industrial activity, including forest management [8]. There is a long history of timber-oriented management in boreal forests, although there are regional variations: extensive management dominates in North-eastern Canada, whereas Fennoscandia mostly experiences intensive forestry [9]. Forest management is intensifying even more due to

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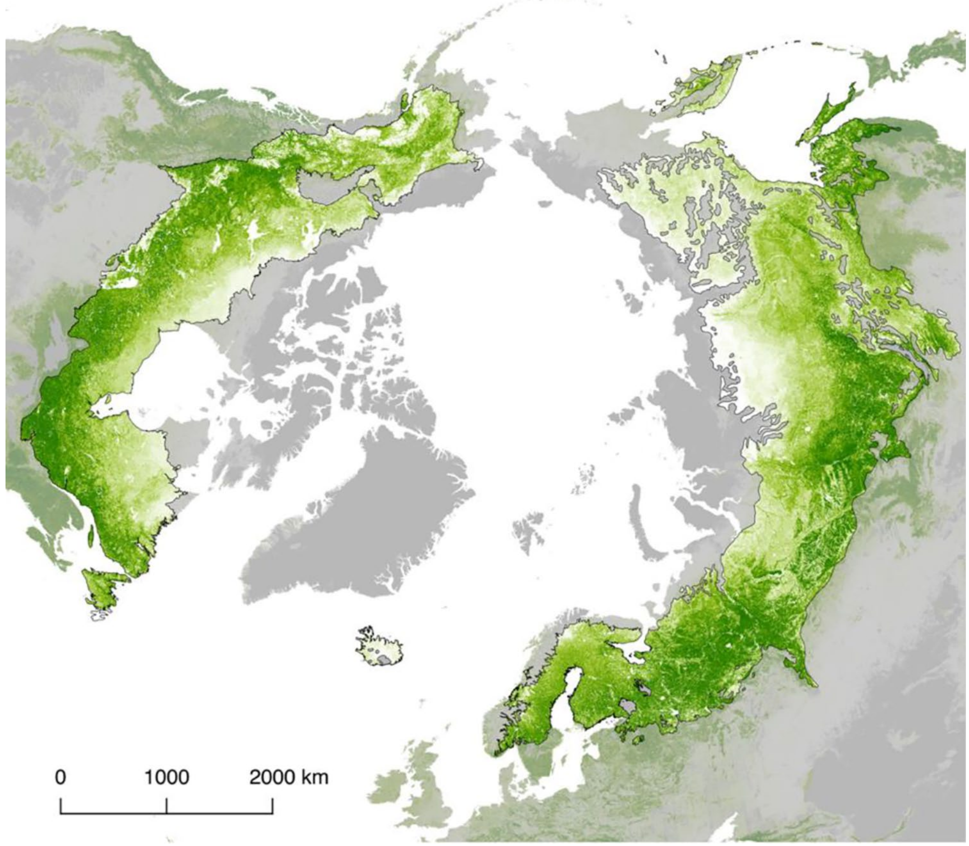

Fig. 1 Map showing the global extent of the boreal zone. Darker green represents denser forest cover (Data source: Global Land Cover Facility, Tree Canopy Cover 2010; figure reused with permission from [5])

the pressure to use forest resources for bioenergy and bioproducts to meet the challenging bio-economy policy goals, which are considered as an important strategy for climate change mitigation [10]. Intensive management can result in mono-specific, even-aged forests with considerable reduction of structures that are critical for biodiversity: presence of large trees, old-growth forest area, deadwood volume and quality, and proportion of deciduous trees [11–13], thus threatening forest biodiversity [14]. Forest management also plays an important role in the provision of ecosystem services [15–18]. For example, diversification of management through modifying the rotation time, frequency, and intensity of thinning at the landscape scale affect timber production and carbon sequestration (e.g., [19, 20]).

Forests ecosystems are increasingly affected by changes in climate and its associated extreme events [21, 22]. Boreal forests are expected to experience the largest temperature rise (4–11 °C by the end of the twenty-first century) of all forest biomes [23]. On the one hand, the direct and indirect cumulative effects of higher temperatures and CO_2 concentrations, and of shifting precipitation patterns, are boosting tree growth and productivity in boreal forests [24]. On the other hand, climate change is expected to increase the frequency, extent, and intensity of extreme events (i.e., windthrows, fires, and insect outbreaks), threatening the forest capacity to provide ecosystem services and suitable habitat for species [22, 25]. Large-scale and severe disturbances may lead to more homogenous forests (e.g., shifting the forest composition towards younger successional stages) [26], detrimental cascading effects (e.g., large-scale wind damage followed by a bark beetle outbreak) [22], and can offset the expected increase in productivity [27].

The combined pressures and impacts caused by intensive exploitation and multiple risks associated to rapid climate change [23, 28] can lead to even less resilient forest landscapes (e.g., [29, 30]). Therefore, several alternative forest management approaches have been suggested to account for and mitigate the increased risks of natural disturbances. Such adaptive forest management planning aims at promoting forest resilience and multifunctionality. Here, we first review the concept of resilience in forest sciences, how extreme events may put boreal forests at risk, and how management can alleviate or promote such risks. Then, we identify and summarize the existing management approaches to enhance forest resilience. Finally, we discuss the future challenges and opportunities of managing boreal forest ecosystem to promote resilience under global change.

Background

The Concept of Resilience in Forest Sciences

The concept of resilience is widely used in ecology. It has evolved considerably since the seminal article by Holling [31], leading to multiple definitions from an engineering to an ecological and socio-ecological point of view (Table 1) [32]. Here, we consider forest resilience as the ability of a system to reorganize itself after an external pressure (e.g., climatic extreme event) while maintaining the same functions, structures, identity, and feedbacks [33]. The pressures could be abiotic (e.g., heat wave) or biotic (e.g., insect outbreaks), which can have synergistic effects [34••]. To understand how forests will respond to future conditions, we need to quantify the interactions between natural and human systems as key determinants of extreme events [35]. Promoting forest resilience is key to adapt to global change [36•] and is frequently mentioned as one of the main goals of forest management and restoration [37, 38].

Forest ecosystems are intrinsically resilient to natural disturbances as they determine the natural succession dynamics of forests. Natural disturbances are key to provide habitat (for early-stage species) and resources (e.g., deadwood), and they are followed by a re-organization phase that allows species colonization (recruitment of new species) and succession [41]. Moreover, large-scale disturbances can provide opportunities to quickly restore some of the resources lost from intensive forestry or even restore habitat types that are currently threatened (e.g., amount of deadwood) [11]. However, the changing disturbance regime (in terms of frequency, severity, and extent) in comparison to their historical occurrence range [42] might endanger the ecosystem's capacity to recover and the ecosystem might collapse [43].

How Extreme Events May Put Boreal Forests at Risk?

Climate change is associated to more severe extreme events, such as longer periods with low precipitation and high temperatures, which could result in widespread reduction in productivity and increase tree mortality (e.g., [44]). There are numerous studies pointing out the positive and negative ecological responses of boreal forests due to climate change and its associated extreme events (e.g., [45–48]). On the one hand, warmer temperatures can prolong growing seasons, and increased atmospheric CO_2 can improve soil fertilization, ultimately increasing forest biomass [49]. On the other hand, extreme events occurring in boreal forests can lead to decreased biomass, such as windstorms [50], insect outbreaks [51], fires [52], recurrent heat waves [46], and severe and/or sequential droughts [53] (Fig. 2). Therefore, climate change can affect tree species productivity and demographic processes such as growth, mortality, and regeneration (e.g., [54]) which can lead to changes in forest composition and structure (e.g., [55]) that determine forest resilience (Fig. 2).

The effects of warmer temperatures on boreal forest productivity are not evenly positive; they benefit forest growth in northern and wetter boreal regions [56] while mostly reduce forest productivity in southern and drier boreal areas [22]. For example, the heat waves in western Siberia in 2012 and in northern central Siberia in 2013 may have substantially decreased forest productivity in Russian boreal forests because of higher temperatures and greater water stress [57]. Water stress caused by droughts is one of the main drivers of large-scale tree mortality and, therefore, will impact the carbon cycle in the boreal region [58]. Indeed, there is evidence of forest dieback in boreal forest in relation with severe drought events (e.g., [58–60]).

Warmer temperatures have also been associated to changes in insect outbreak regimes, both directly (e.g., new species coming from temperate zone and expanding into the boreal biome) and indirectly (e.g., increasing their capacity to spread

Table 1 Definition and characteristics of the three most common and frequently used resilience definitions in forest sciences (see [36•, 39•])

	Engineering	Ecological	Socio-ecological
Brief definition	Return to a single equilibrium state after a recovery time period	Maintenance of the main functions, services, and structures, potentially as an alternative state	Maintenance of functions, services, and structures and the adaptive capacity of a coupled human-natural system
Equilibrium state	Single	Multiple	Multiple
Temporal extent	Short	From years to centuries	From years to centuries
Spatial extent	Short	Diverse range	Diverse range
Examples of indicators	Basal area increment Vegetation cover Species composition Biomass	Primary production Nutrient cycle Regeneration Mortality	Socio-economic diversity Biodiversity Stocks of natural resources Ecosystem services
Key reference	Pimm [40]	Holling [31]	Walker et al. [33]

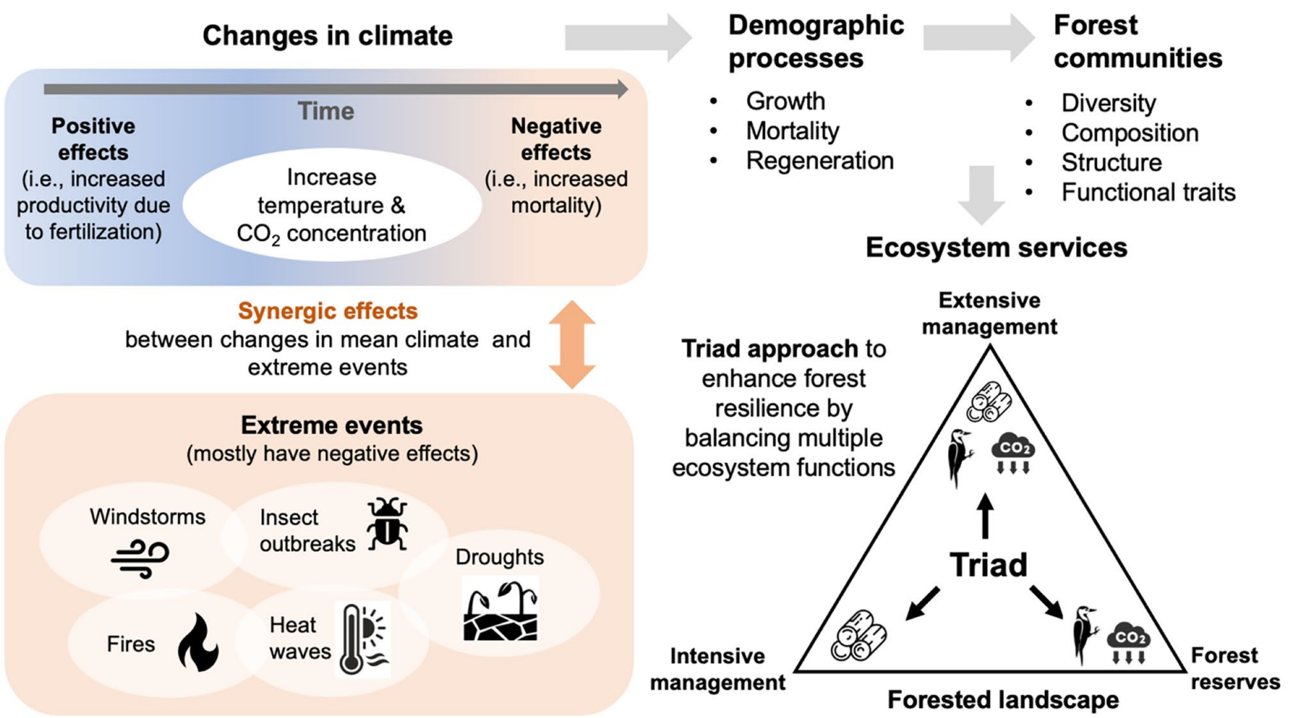

Fig. 2 Conceptual figure summarizing the interactions between changes in climate and extreme events, determining demographic processes, forest communities, and ecosystem services. We added an example of how the Triad functional zoning approach can help to enhance forest resilience

because of weakened trees after a storm) [22]. Chen et al. [51] observed that warmer early spring temperature rather than droughts could promote insect outbreaks, suggesting continued warming springs may worsen growth decline and dieback events in North American boreal forests. Trân et al. [61] showed that the most relevant climatic driver controlling the population of bark beetle was low temperatures during the coldest part of the winter. With the right environmental conditions, bark beetle numbers can swiftly increase as warmer temperatures enable them to reproduce faster and produce two generations per year instead of one as currently [62].

In addition to the above-mentioned risks, large wildfires in western North America have increased in recent years, a tendency that climate change is likely to aggravate [52, 63–65]. To meet this challenge, long-term adaption approaches to mitigate wildfire risk are needed, especially in areas with high fire risk. Techniques to mitigate wildfire risk include adaptive silvicultural approaches [66], wildfire responses [67], or proactive controlled burning [68]. This change in wildfire risk may be different across boreal zones, as Drobyshev et al. [69] found that while fire hazard in spring increased in parts of North-West Russia, this trend did not seem to be reflected in European boreal forests.

It is important to have a holistic view and consider jointly different disturbance types because they can accumulate over time and space. For instance, drought affects more strongly post-fire young forests than mature forests in Siberia, delaying their recovery [70]. As a result, very large areas of the boreal forests may experience at least one type of natural disturbance in the future (e.g., in Canada [30]). Inadequate management and lack of preventive mitigation actions may worsen the accumulated pressures and lead to widespread regeneration failure and changes in ecosystem state and dynamics [43, 71]. For example, more frequent fires can lead to post-fire recruitment failure and forest loss [72–74]. In particular, a lack of anticipation in increased natural disturbances may lead to overharvesting [29, 75], which in combination with increased natural disturbance pressures may generate "landscape traps" and possibly ecosystem collapse [43, 76]. Due to natural disturbances such as fire and insect outbreaks are spatial processes (contagions), landscape homogenization and impaired ecological functions caused by human and natural disturbances may lead to feedback loops and cascading effects that further increase disturbance risks [76].

How Can Management Practices Alleviate Risks or Make Them More Severe in Boreal Forests?

Forest management can alleviate or increase risks and promote the resilience of forests stands to maintain the provision of ecosystem services and biodiversity. Forest practices can be split into management aiming at achieving long-term adaptation (i.e., anticipating disturbances) and short-term adaptation (i.e., recovering from disturbances).

Long-Term Adaptation: Anticipating Disturbances

Long-term adaptation involves promoting stand resilience before disturbances occur while maintaining main forest ecosystem functions and services. The main management actions to increase long-term adaptation are increasing species compositional, functional, and structural diversity (i.e., tree age, size, height) [77]. Compared to monospecific forests, forests with more tree species increase multifunctionality (i.e., simultaneous provision of high levels of multiple ecosystem services and species habitats) [78], can be more productive [79], and are resistant to many natural disturbances and climate change [80]. For example, inclusion of birch trees within pure Norway spruce forests stands can reduce the volatile attractive to bark beetles and reduce the risks of bark beetle outbreaks [81]. Ikonen et al. [82] showed that planting Scots pine or birch after a clear-cut, rather than Norway spruce, reduced the probability of wind damage because lower wind speed is required to damage spruce compared with pine or birch of the same size.

Delaying or excluding thinnings can promote carbon storage (e.g., [19, 20]) and formation of deadwood [83], which is a key resource for many endangered species [84]. Asynchrony of final harvests over time and space can limit the spatial aggregation of the clear cuts and reduce newly exposed edges that are the most susceptible to wind damage [85]. Increasing share of uneven-aged forestry over the landscape can increase multifunctionality [7, 86, 87] while reducing overall wind damage in case of windthrows [88, 89].

Long-term adaptation also requires proactive approaches to reduce fire risk, which is one of the most important natural disturbances in the boreal region and which is expected to increase strongly because of climate change [73, 90]. The main strategies to reduce fire risk include modifying the vegetation composition [91], reducing the fuel available to burn by harvesting the forest [92], or promoting the use of fire-resistant species [93]. Even tree species well-adapted to fire risks may suffer from increased frequency and severity of fires. The retention of coniferous trees during harvest can ensure that a sufficient seed bank is available to regenerate a stand adequately if it burns before the post-harvest new cohort reaches reproductive maturity, thereby increasing stand resilience to fire and avoiding the need for reforestation [71].

Short-Term Adaptation: Recovering from Disturbances

Salvage logging (i.e., removal of damaged trees) is a common management practice used after a disturbance to mitigate economic losses. However, wide-scale application of salvage logging can be detrimental for ecosystem services and biodiversity and can act as a second disturbance for some ecosystem processes (e.g., carbon sequestration, accelerated soil drying) [94, 95]. Salvage logging may even increase future risks, e.g., fire risk, if a large amount of dry wood debris is left on site [73]. In addition, the use of salvage logging as a mean to prevent bark beetle outbreaks has been shown to be rather ineffective under climate change [81, 96, 97]. Salvage logging has higher harvesting and logging costs compared to undisturbed stand [98], especially in areas with low accessibility [81], and cannot fully compensate for timber losses [75]. Therefore, we suggest considering carefully salvage logging at large spatial extents after disturbances, focusing on social and ecological objectives in addition to economic priorities.

Post-disturbance treatments have also a strong influence on forest regeneration, which is a crucial aspect of recovery and represent opportunities to develop future resilience capacity. Salvage logging affects the regeneration process by removal of mature tree and their aerial seed banks, increased soil drying, and mechanical damages to saplings [94]. As a consequence, it modifies and homogenizes species composition (e.g., promoting trees with vegetative regrowth) and may increase the risks of regeneration failure. Post-disturbance reforestation may be used to boost forest recovery and prevent regeneration failure after intense or repeated disturbances, using tree species that are better adapted to fire, drought, insect outbreaks, or wind damages [71]. Post-disturbance tree planting may also be an opportunity for assisted migration to introduce new tree species or genetic variants that are adapted to expected future conditions or that will increase functional diversity [34••, 77, 99].

To enable coherent decisions, we suggest setting long- and short-term management objectives to ensure the maintenance of forest ecosystems services and biodiversity. Achieving a high adaptation to climate change will require accounting for disturbances into the long-term forest planning and increase social resilience of the local forestry sectors and forest economics [34••, 77, 99, 100••]. Not considering impacts from disturbances when planning will lead to an optimistic expectation for economies revenues [71, 101], leading to further imbalances when managing forests for both economic and ecological objectives. In addition, the occurrence of disturbance events is unpredictable and often requires quick actions. Therefore, it is crucial to have appropriate forest policies and short-term adaptation strategies on how to deal with them (e.g., [11]).

Management Approaches to Enhance Resilience in Boreal Forest Landscapes

The main approaches proposed to manage boreal forests at the landscape level range from natural forest emulation and functional zoning to functional network and climate-smart forestry (Table 2). While we recognize that the original goals of these management approaches were

Table 2 Comparison of the basic properties of the main forest management approaches in the boreal zone

	Natural disturbance emulation	Landscape functional zoning	Functional complex network	Climate-smart forestry
Main concept	Reproduce the structural variety of natural forests through management to enhance biodiversity and ecosystem functioning	Combine intensive and extensive management, and forest reserves to increase landscape multifunctionality	Promote tree species functional diversity through stand-level enrichment and landscape connectivity to enhance forest adaptive capacity	The main focus is on climate change mitigation by increasing carbon sequestration and storage by trees and wood products
Consideration of disturbances	Disturbance regimes are used as a reference to guide management; extreme events are not explicitly included	Can be used to determine the proportion of extensive, intensive, and protected areas	Disturbances can be mitigated and recovered through tree species functional diversity	Improve resilience of forests to disturbance and focusing on biomass production in areas subject to a high risk and quality wood production in areas with low risks
Ecosystem services	A semi-natural state of the forest maintains ecological processes and its associated services	Conflicting ecosystem services can be provided at the landscape level	Resilient forest ecosystems can maintain their functions under unpredictable event	Using wood resources for climate change mitigation in combination with enhancing other forest ecosystem services
Adaptation to climate change	Disturbances are opportunities for ecosystem reorganization and adaptation	A diversity of extensive management and tree species diversity in plantations offers opportunities for adaptation/will be more resilient	Forests are considered as complex self-organizing systems, conditional on structural and functional diversity	Enhancing health and resilience of forest by adaptive forest management
Regions mostly used	Fennoscandia (ASIO model) Canada (EBFM approach)	North America (Triad approach)	Canada	Europe
Key reference	Berglund and Kuuluvainen [106••] Gauthier et al. [107]	Himes et al. [113••]	Messier et al. [34••]	Bowditch et al. [108••]

not necessarily to promote forest resilience, we anticipated these approaches would improve forest resilience and ecosystem services. Although all these approaches have attracted a lot of interest in the last decades, most of them remain largely theoretical as they have been mainly assessed using simulations. There are few exceptions to this; for example, the Triad approach has been applied in some forest landscapes in Canada [102], and it will be also tested at the Elliott State Forest (32,000 hectare) in southwestern Oregon constituting the largest forest study in the USA [103]. Another exception is the ecosystem-based forest management (an example of the natural disturbance emulation) that is applied on all public forests in Quebec (i.e., about 92% of the 905, 800 km^2 of Quebec forests) [104]. In this section, we shortly summarize the practical and conceptual foundations of each of the approaches and critical points towards the boreal forest resilience.

We acknowledge that adapting forest management to climate change and enhancing forests resilience is a fast growing field of research and we do not exhaustively cover all existing frameworks. A couple of relevant examples not explicitly included within the discussed management approaches are the framework by Nagel et al. [105] and Nikinmaa et al. [99]. On the one hand, Nagel et al.'s framework includes no action, resistance, resilience, and transition strategies; the resistance are similar to mitigation actions, while the resilience and transition strategies can be considered adaptation actions [105]. On the other hand, Nikinmaa et al. propose a framework which includes a participatory process with stakeholders as an important step towards operationalizing social-ecological resilience of forests [99].

Natural Disturbance Emulation

The natural disturbance emulation approach postulates that forest management should aim at reproducing the structure of natural forest, i.e., resulting from natural disturbances, to maintain and restore forest ecological conditions [41, 100••, 109]. The approach is based on the hypothesis that mimicking natural tree mortality patterns at multiple scales will recreate forest structures that support biodiversity and ecosystem functioning and thus ecosystem services. A diversity of management actions is needed to reproduce the natural range of habitat variation and is expected to maintain various forest services, such as carbon sequestration and recreation.

An example of this approach is the ASIO model (acronym from the "Absent, Seldom, Infrequent, and Often" typical fire regimes), a guide for forest managers initially created in the 1990s and updated as knowledge of the forest system develops. ASIO aims to explain how the combination of natural fire frequency and gap dynamics affect the structure of European boreal forests, assuming that site type is the main determinant of natural disturbance dynamics [110]. The resulting management model may be easily implemented at the stand level and scaled up to landscape or regional levels [106••]. Based on known disturbance frequencies and site type distributions, Berglund and Kuuluvainen [106••] estimated the proportion of forest dynamic types and forest age classes in Fennoscandian forest landscapes, which should serve as guideline for application of management strategies locally (using a combination of even- and uneven-aged forestry). Using the natural disturbance emulation guidelines emphasized a lack of young deadwood-rich and old forests in commercial Fennoscandian and North American landscapes, as compared to the expected level in landscapes without human operations [9]. This implies that the timing of harvests and the post-harvest legacies (live or dead trees) are important besides the management style (even- vs uneven-aged forestry) [100••].

Originally the natural disturbance emulation approach did not explicitly refer to climate change adaptation or extreme disturbance events. However, the ecosystem-based forest management (EBFM), which represents another example of this approach [111], can help to enhance forest resilience under climate change conditions [112]. Moreover, in response to the criticism that current natural forest references may depart from the future state under climate change, it has been argued that the creation of landscapes with complex and heterogeneous habitats would increase the resilience and adaptive capacity for forest ecosystems [100••]. Indeed, promoting native biodiversity (including functional diversity) and post-disturbance legacies (e.g., canopy openings and deadwood) should support ecosystem self-reorganization and maintain key ecological functions. The natural disturbance emulation approach could also account for increased extreme events in the management plan by considering that young successional stage will be generated by such events, while the conservation of late successional stages might be prioritized (e.g., [29]).

Landscape Functional Zoning

The landscape functional zoning management approach emphasizes the need to mitigate the potential conflicts between multiple socio-ecological objectives (timber production, biodiversity conservation, and non-wood ecosystem services) by allocating specific priorities to selected forest area that are managed to achieve them, thus, enhancing landscape multifunctionality [113••]. The main example of this approach is the Triad model, which refers to management at the landscape level composed of three zones: (1) intensive management focusing on timber production, (2) protected areas (i.e., reserves) aiming at biodiversity conservation, and

(3) a matrix of forests extensively managed for multiple purposes [34••, 114]. The rationale behind the Triad approach is that extensive (ecological) forest management cannot fully replicate the forest structure of natural forest, and, therefore, some unmanaged "natural" forests is required to safeguard overall biodiversity. In addition, the introduction of intensive, highly productive plantations can be used to satisfy timber demand, allowing for larger areas to be protected.

The landscape functional zoning approach can be seen as a combination of land sparing and land sharing; however, the relative benefits of each management zone is likely variable across regions [115]. In that sense, the Triad approach is flexible in terms of the proportions of the landscape allocated to each zone and may adapt to local historical and ecological conditions and to the priorities and preferences of forest owners and stakeholders. For example, in a Canadian landscape, Côté et al. [116] found that the Triad scenario with 12% forest reserve and 60–74% extensive management outperformed the status quo and a governmental plan in terms of biodiversity outcomes, without losses in harvesting volumes.

The Triad approach acknowledges the need to consider the uncertainty associated to climate change in each of the forest management zones. First, extensive management in forest reserves might be needed to promote forests adaptation to new conditions, e.g., facilitate migration of tree species or prevent insect outbreaks [113••]. From this perspective, no action might lead to ecosystem collapse and shift to undesirable state [43]. Second, multi-species plantations should be preferred over monocultures to ensure long-term adaptability and productivity [77]. Such more structurally complex and intensively managed forest could also provide ecosystem services to some extent. Third, Himes et al. [113••] highlight the value of management diversification in the extensive zone for testing novel management practices, as well as reducing overall risks, i.e., structural diversification of management across the landscape should support more adaptive and resilient forest systems.

Functional Complex Network

The functional complex network approach is based on stand-level functional and structural diversity and landscape-level connectivity as key forest characteristics for resilience towards climate change and extreme events [34••, 117•]. This approach acknowledges uncertainties and the necessity to manage forest as complex adaptive systems, capable of self-(re)organizing, e.g., through natural regeneration. Following the principles of the insurance hypothesis from functional ecology, tree species functional diversity and redundancy are expected to promote forest adaptive capacity and maintain forest functions, hence supporting resilience. However, high tree species richness does not always correlate with high functional diversity, which can compromise resilience [118]. The second essential aspect of the method is to develop landscape connectivity to facilitate seed dispersal and migration of tree species, which would support functional diversification (potentially even using assisted migration) [117•].

The objective of the functional complex network is to favor or plant tree species to maximize stand-level functional diversity or to add specific functional traits known to enhance resilience towards predictable stressors (e.g., drought) [34••, 119]. In practice these actions may include planting tree species from rare functional groups or harvesting tree species from predominant functional groups [118]. Emphasis is also put on the spatial organization of management as these interventions are meant to be strategically located in the landscape to increase their long-term impact at the landscape level [117•]. Spatial habitat network analyses should be used to identify forest stands with high centrality, i.e., stands that can potentially lead to high dispersal of implemented trees and functional traits. Such targeted functional enrichment is expected to ensure rapid colonization and self-reorganization of disturbed stands, swift regrowth of diverse tree communities, and thereby, increase long-term forest resilience [34••, 117•, 119].

The functional complex network can be used to evaluate the current state of forests and test the potential outcomes of new management practices or management scenarios by combining simulation models of forest growth, management, and disturbances. Specifically, Aquilué et al. [119] found that enrichment of less functionally diverse forest patches effectively increased functional diversity and connectivity and resulted in forest landscapes more resistant to drought and insect outbreaks. In addition, Mina et al. [117•] found that the functional complex network analyses allow creating forest landscape that tolerate better insect outbreaks and maintain productivity and carbon storage, as compared to business-as-usual management or climate adaptation management (i.e., without spatial prioritization of functional diversification actions).

The functional complex network is quite a recent approach. It builds on the widespread concept of green infrastructure, which aims at the spatial planning of interconnected networks of habitats to support biodiversity and ecosystem services. For example, Andersson et al. [120] applied this framework to the network of old forest types in Sweden and the provision of recreational services to map and prioritize forest conservation and forestry operation.

Climate-smart Forestry

Climate-smart forestry is an emerging branch of sustainable forest management. The overall objective is to manage forests in response to climate change by promoting forest growth, increasing carbon sequestration, and reducing carbon emissions from non-renewable resources [1, 108••]. The climate-smart forestry approach uses adaptive management to increase the forests' resilience to a range of climate change scenarios and climate-induced disturbances. The mitigation of climate change by forests can be achieved by enhancing carbon sequestration by trees, carbon storage in wood products, and carbon substitution (i.e., by replacing fossil fuels with bioenergy and by using wood to substitute for higher carbon footprint materials) [121]. The speed and efficiency of these processes depend on the environmental conditions affecting tree growth (e.g., climate, soil type), the type of forests (e.g., species composition and structure), and forest management regimes [122].

Even if initially the main aim of climate-smart forestry was the mitigation of climate change, this approach has evolved to include adaptation measures and the social dimension of forestry. The adaptive capacity of the forests can be improved by promoting compositional, structural, genetic, and functional diversity at both stand and landscape levels. This consists of benefiting from natural regeneration, increase connectivity to assist migration of forest species and planting tree species, and genetic variants that are better adapted to warmer and drier conditions as well as to extreme events [108••].

Timber harvesting conflicts with carbon sequestration and may cause the release of CO_2 to the atmosphere from disturbed soil [123]. Therefore, the most suitable timber harvesting practice for climate-smart forestry is uneven-aged management, avoiding clear-cut areas in the forest stand. This selective system of timber harvesting, if done properly and repeatedly, results in the forest with a diverse canopy structure, high age diversity, and good potential for self-restoration. Thus, climate-smart forestry promotes mixed species forest stands or a mosaic of forest stands with a diversity of structures and species [124].

Future Challenges and Opportunities

Integration of the Different Approaches into Ecological and Resilient Forest Management

The main management approaches presented above (Table 2) share aims and have many elements in common. For example, the landscape functional zoning can incorporate many different management styles aiming at balancing ecological and social objectives, including some practices inspired from natural disturbance emulation and from climate smart forestry [113••]. In addition, the natural disturbance emulation and the landscape functional zoning approach can both be seen as a combination of land sparing and land sharing, where different management intensities are used across the landscape to create different forest structures and meet multiple objectives [100••, 115]. Another common feature to all approaches is management diversification and functional diversity which are needed to create structural variation in the landscapes and enhance forest resilience and multifunctionality [7, 18, 125]. Thus, we argue that the complementary strengths from all these approaches need to be integrated to develop complete and flexible forest guidelines for the Anthropocene. However, we are still missing a way to integrate them at an appropriate scale, where a combination of approaches could be optimized to enhance multifunctionality, while at the same time dealing with uncertainty and increasing or maintaining forest resilience to global change [34••]. Another challenge is to make adequate stand-level decisions from a potentially very large portfolio of management options while accounting for landscape-level objectives and processes.

Even if the discussed management approaches provide some general guidelines, there is a need to account for the regional differences when applying these approaches. For example, the main climate-induced disturbances differ across regions; while recent large wildfires have mostly affected forests in Siberia and Canada (e.g., [73, 126]), severe windstorms, heavy snow loading, and insect outbreaks have caused major forest damages in Fennoscandia [22, 127, 128]. Spatial configuration such as a landscape connectivity also plays an important role. Tree species could be able to track climate change in well-connected regions [129] whereas assisted migration might be needed in more isolated regions (e.g., Fennoscandia) or for species with poor dispersal abilities [130]. Thus, different regions will require different adaptation and mitigation strategies according to their specific risks, spatial, and ownership characteristics.

All the management approaches discussed above can be combined with multi-objective optimization [131], which provides a flexible approach to produce and compare the outcomes of individual management scenarios that consider different objectives and constraints. In addition, multi-objective optimization could be used to identify the optimal combination of management regimes for enhancing forest multifunctionality and resilience under global change. Through a simulation and multi-objective optimization framework, Pohjanmies et al. [132] assessed the resilience of boreal forests after intensive harvests. They found that forest multifunctionality was substantially decreased under intensive forest management and that forest multifunctionality was not resilient to intensive forestry. The justification is that the forest recovers slower when intensive forestry is applied for a longer time. Another example for improving long-term management planning was shown by Blattert et al. [86] who combined multi-objective optimization with forest governance research and provide novel insights into the design of Finnish forest management. Authors designed scenarios to study the effects of forest policies on forest management and the resulting trade-offs among forest ecosystem services. All scenarios suggested major changes in current boreal forest management compared with the current practices to meet the policy demands for ecosystem services. Their outcomes provide leverage points for better integration of multiple ecosystem services in future policies to overcome socio-ecological land-use conflicts in forests. The full integration of the multi-objective optimization and spatial prioritization requirement currently still faces computational and methodological challenges (but see [133, 134]). The importance of spatial organization and habitat connectivity are emphasized in both the Triad and the functional complex network approaches, as a means to maintain biodiversity and ecosystem services and facilitate the dispersion of tree species and their functional traits [34••, 113••].

Implementation: Planning and Just Governance

Forest management planning requires clearly defined objectives to allow for its practical implementation. Yet, identification of the reference conditions (defining the natural state and typical disturbance regime) can be challenging due to lacking natural reference system, unknown historical disturbance regimes, or inability to distinguish between human-made and natural disturbances due to long-term co-evolution [100••]. To overcome those challenges, we need, firstly, to apply adaptive and flexible management guidelines that take natural disturbance regimes into account. This includes more realistic harvest prospects that account for the inevitable timber losses due to increased natural disturbances [43, 75]. The desired variation in forest structure across the landscape can be obtained by using variable cutting patterns which can be performed with existing sophisticated machinery [100••]. Secondly, the implementation of management plans critically needs to shift from stand- or small-scale to landscape-level management planning to better address conflicting objectives [135]. Lastly, we need to improve the framework for an efficient implementation of advanced computational methods such as multi-objective optimization to evaluate complex outcomes of different management scenarios [136].

The implementation of novel managements requires fair governance structures and mechanisms to direct the decisions [137]. Regulative, financial, and informational instruments that limit transition towards more resilient forest systems need to be updated. Forest policies have been often biased towards specific sector interests or views, bringing upon increasingly heated debates [138]. For instance, uneven-aged forestry was forbidden for decades in some north European countries [138], or official management recommendations have been biased towards specific practices [139]. These governance instruments affect societal norms that are now challenging to shift swiftly. Inclusive and balanced discussions with stakeholders with transparency on the consequences of management options is essential, not only for more democratic processes but also to better engage stakeholders into novel practices. It is important that landowners agree on the new management goals and that the management actions are logistically and economically feasible [34••]. Forest ownership varies quite much among countries: about 90% of forests are publicly owned in Canada [140], whereas in Finland, private individuals govern 60% of forest land [141]. Thus, private forest owner preferences can dictate to which extent a change in forest management paradigm is achievable. However, it can be challenging to coordinate forest management with multiple forest owners with different backgrounds and objectives. Facilitation of coordinated action towards novel conditions and stronger resilience require holistic planning of training and incentive schemes to effectively improve the capacity of stakeholders.

Moreover, the boreal region hosts a great diversity of local and Indigenous communities that depend on forest ecosystem services for their well-being and cultural integrity [142]. With this, local and Indigenous communities have culturally embedded multifunctional use of forests; for instance, in northern Fennoscandia, Sami reindeer herders have been using for centuries forests for collectable goods, timber resources, and foraging for reindeer. Traditional knowledge of alternative values of forests and their resilience can provide invaluable insights [143]. The involvement of local and Indigenous communities in forest governance have increased since the 1980s, but they are still facing challenges to have a real influence of forest-related decisions and to get tangible benefits from timber harvesting [144].

Inclusion of participatory processes influencing forest management is becoming more commonly established, such as co-designing mitigation actions with stakeholders [99]. For instance, several EU directives, national policies, and forest certification schemes (e.g., FSC, PEFC) require consultation of stakeholders when defining objectives and actions [145, 146]. Nonetheless, how participation is integrated into final decisions and whether power structures between stakeholders have been taken into account is yet far from transparent [145]. Only when all players in the socio-ecological system are properly acknowledged and their views and values are integrated into management decisions will forestry be able to keep the “license” to operate in the long run [34••].

Lack of Empirical Evidence and Tools to Monitor Resilience

We currently identify two main limiting factors to evaluate the discussed management approaches from the practical and methodological perspectives. There is a general lack of experimental settings to monitor and test how efficient are the different approaches to achieve their main goals due to long-term development of forest ecosystems. The large-scale experimental case study for the "Triad" approach, recently proposed for the Elliott State Forest in Oregon (USA) [103] will provide one of the first empirical evidence of implementing landscape functional zoning into practice. The research site will be split into sub-watershed areas with each sub-watershed applying a specific combination of intensive reserves and multi-use forests with a replicated design. A common objective is to obtain an equal supply of timber from sub watersheds under different management plans. Yet long-term observation and evaluation of this practice is needed to fully understand the opportunities and limitations of the Triad approach.

There have been several efforts in monitoring the effects of climate change on forests such as the Adaptive Silviculture for Climate Change (ASCC) project in USA which established long-term research sites across the country to assess a range of adaptation management regimes [105]. Moreover, data from National Forest Inventories could be used to assess the effects of climate change (e.g., [49, 147]). However, we still need more guidance and good indicators to develop and implement long-term monitoring and evaluation schemes of forest resilience [36•]. There is high uncertainty and limited ability to predict future forest responses to global change mainly due to the unknown future socio-economic path of humans and the complex interactions among different pressures. Thus, the best strategy to deal with an uncertain future is to combine different approaches for different situations and consider management practices such as assisting species migration, increasing landscape connectivity, or species composition and genetic diversity [148]. Moreover, there is a need to incorporate stochastic variability in the projections of forest planning models to deal with uncertain future ecosystem conditions [149]. For forest managers to be able to adapt to uncertainty, decision support tools should identify actionable management options to reduce risk. This requires understanding of what sources of uncertainty are important to the forest managers and the options available to mitigate the risk [150]. Finally, in addition to prioritizing management according to specific guidelines, systematic monitoring of conservation objectives is essential. To ensure consistent and sustainable timber resources, foresters have established long-term national-level monitoring (i.e. [151]). Similar intensive long-term data collection and monitoring approaches should ensure environmental sustainability. Even with increased data collection, special attention should be made to avoid quantitative fallacies [152], by acknowledging the importance of environmental issues that may not be easily measured. Evaluating the long-term impact of environmental change and potential adaptations could be addressed with the help of simulation models, which have become pivotal tools in forest resilience research [39•].

Conclusions

The negative effects of climate change on boreal forest ecosystems are increasing over time due to the combined effects of increased warming and extreme events. Recent new approaches to forest management can prepare the boreal forest to mitigate the impacts and uncertainties of global change. The reviewed management approaches share common aims and practical elements, all highlighting the need for management diversification, increase structural and functional diversity, and a reduction of human pressures. Landscape planning, i.e., careful spatial organization of management actions, is also considered as one of the key elements to increase the adaptive capacity and resilience of boreal forests. However, specific practical guidelines and anticipation of future changes are crucial to implement short- and long-term social-ecological adaptations. Adaptive boreal forest management requires clear objectives and inclusive debate across forest stakeholders to develop shared, acceptable, and flexible solutions that go beyond prioritizing economic objectives, to the benefit of social and environmental objectives.

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Compliance with Ethical Standards

Conflict of Interest Any author has no conflicts of interests to declare.

Human and Animal Rights and Informed Consent This article contains no studies with human or animal subjects performed by the authors.

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- •• Of major importance

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