Chapter 1
Ecosystem Management of the Boreal Forest in the Era of Global Change

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1.1 Introduction

The boreal forest is a vast biome encompassing approximately one-third (30%) of the world's forest area. It harbors about half of the world's remaining natural and near-natural forests and provides important ecological, economic, social, and cultural services and values that benefit human communities (Burton et al., 2010; Gauthier et al., 2015a). Although the diversity of tree species in boreal forests is low relative to that of other biomes, the forests' structural and compositional variability and the diversity of ecological interaction networks are high (Burton, 2013; Isaev, 2012, 2013; Kuuluvainen & Siitonen, 2013). The genetic diversity of tree species is generally high with most species being wind pollinated and characterized by large population sizes; this genetic diversity provides a foundation for an adaptive capacity in the face of fluctuating environmental conditions and ongoing climate change (Aitken et al., 2008).

Landscape diversity in the boreal biome reflects the influence of site variation, the effect of natural disturbances of varying type, severity, and extent, and the resulting

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dynamic processes of ecosystem succession (Fig. 1.1; Chap. 3; Kneeshaw et al., 2018; Shorohova et al., 2011). Fire, insects, wind, beaver, and severe drought events are among the most important natural disturbances in the boreal forest (Chap. 24; Girardin et al., 2006; Johnson, 1992; Labrecque-Foy et al., 2020; Lavoie et al., 2021). Because the boreal biome is located at northern latitudes, it is subject to more rapid and severe effects from climate change than more southern forests. The boreal forest is already affected by changing climate as evidenced by drought as well as fires and insect outbreaks being more frequent and severe (e.g., Hanes et al., 2019; Navarro et al., 2018b; Safranyik et al., 2010; Seidl et al., 2017; Chap. 9). High-latitude regions are associated with cold climates and short growing seasons; thus, tree growth and decomposition processes are relatively slow (Chap. 11). This slow decay of organic matter results in a large stock of deadwood and carbon in the soil. Therefore, the boreal zone can have substantial disturbance-related feedback effects on CO_2 emissions (Chap. 10; Ameray et al., 2021; Bradshaw & Warkentin, 2015; Pan et al., 2011).

Although human population density in the boreal forest is low, two-thirds (2/3) of forested boreal regions are under some form of management, mainly for wood production. These forests account for 33% of lumber and 25% of paper products within the global export market (Burton et al., 2010). In the latter decades of the twentieth century, increased concerns about the effect of forest management on ecosystem functioning, the loss of biodiversity and a change in social and cultural values toward forests drove a paradigm shift toward an ecosystem approach (EA) to forest management (Franklin, 1997). Forest ecosystem management (FEM) principles have since been adopted in many jurisdictions in the boreal forest (Gauthier et al., 2009; Perera et al., 2004; Shvidenko et al., 2017).

Today, however, we are challenged with implementing FEM approaches in the context of global climate change, which affects tree growth and regeneration, causes dieback due to drought, and favors more frequent and severe natural disturbances (Gauthier et al., 2015a). Forests are also increasingly affected by the cumulative impacts of previous management practices, disturbance by other industries, and the consequences of other stresses (e.g., pollution). Hence, there is an urgent need to revisit and adapt the FEM concept to address these new and often synergetic challenges.

In this introductory chapter, we provide the background and context for understanding the emergence and evolution of forest management paradigms. We define the FEM concept and describe the approaches undertaken in its implementation to manage/restore boreal forests within different regions. We then set the stage for discussing the potential effects of global change and the suggested paradigm shifts to FEM.

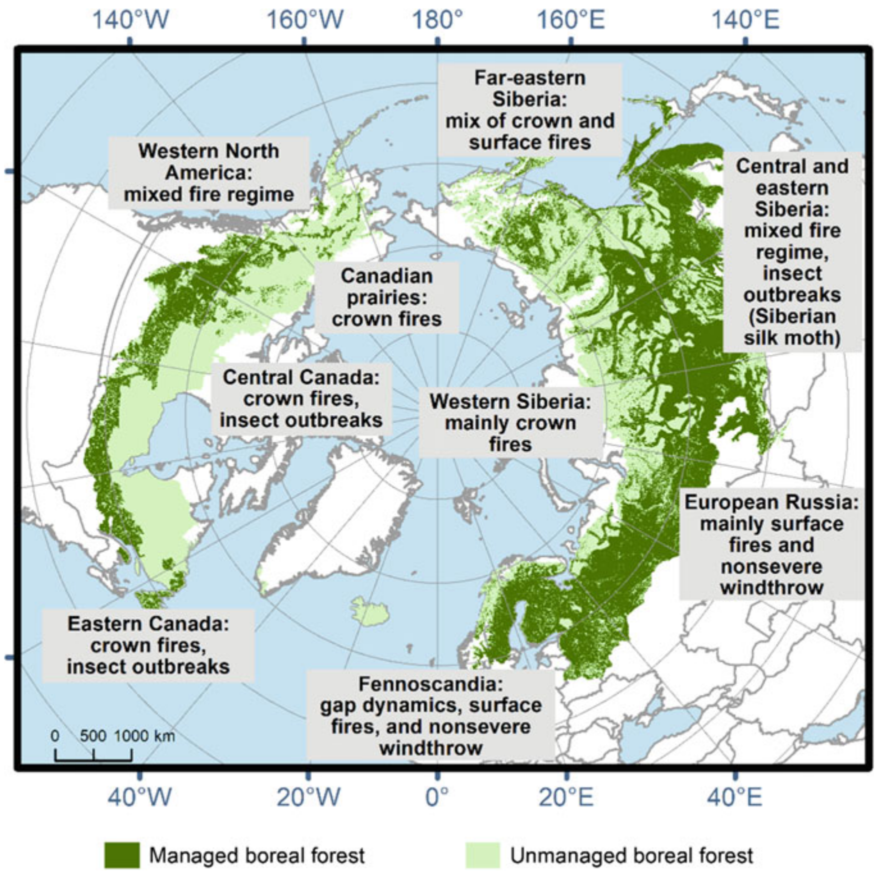

Fig. 1.1 The main disturbance dynamics within the boreal forest regions. Understanding natural disturbance dynamics and their ecological roles is indispensable for forest ecosystem management. Modified from Gauthier et al. (2015b; Reprinted with permission from AAAS) and Shorohova et al. (2011; CC BY-SA 4.0 licence)

Box 1.1 Forest Management Approaches Referred to in This Book

Sustained yield management (SY) Sustained yield management focuses on ensuring a continuous supply of resources (typically timber) that can be exploited over the long term. In the boreal forest, it often entails applying even -aged management and regulating forest age structure to ensure a constant, even flow of timber. Although sustainable forest management (SFM) aims to maintain more ecosystem services than SY, the SY paradigm remains part of forest ecosystem management (FEM) in many parts of the managed boreal biome (Luckert & Williamson, 2005).

Forest ecosystem management (FEM) Both SFM and EA approaches have been crucial in shifting the dominant paradigm of FEM at the beginning of the twenty-first century. Across regions of the boreal forest, FEM has evolved differently because of differences in historical and management contexts.

Natural disturbance–based management (NDBM)/Natural range of variability (NRV) The NDBM/NRV approach developed in North America aims to maintain resilient ecosystems by establishing management approaches on a solid understanding of natural disturbance regimes (NDBM). The presumption is that, despite human management and use, forests will maintain their key intrinsic structures, species communities, and ecological processes. In turn, this approach supports maintaining a continuous flow of the desired ecological, social, and economic values. The approach is based on the idea that current forest ecosystems have evolved under specific disturbance regimes (fire, insects, wind, etc.) that have driven forest dynamics, species composition, and overall biodiversity at the genetic to landscape scale.

Attention has been given to regimes prevailing before European colonization to identify the reference conditions for implementing NDBM and during analogous climates experienced at various periods in the Holocene (Chap. 2; De Grandpré et al., 2018; Gauthier et al., 2009; Landres et al., 1999; Montoro Girona et al., 2018b; Morin et al., 2009; Navarro et al., 2018a, b; Swetnam et al., 1999). These efforts aimed to define a baseline upon which the current state of regional forest landscapes can be compared while considering the inherent variability induced by these regimes. The framework is based on characterizing the NRV of several elements of the disturbance regime, such as disturbance type, frequency, size, spatial pattern, severity, and specificity, and then using this knowledge as a guide to implementing management strategies that will maintain the health of the ecosystem (Keane et al., 2009; Landres et al., 1999; Montoro Girona 2017). This approach permits comparing managed and natural ecosystems and landscapes (Grondin et al., 2018) and helps establish management or restoration targets (Fig. 1.2).

FEM also often involves using a combination of *coarse-* and *fine-filter* approaches. Coarse-filter strategies are implemented on a large spatial and temporal frame of reference, i.e., larger than the stand level, with the understanding that the time/space continuity is essential for some attributes. The coarse-filter approach aims to maintain the various forest habitats representative of natural forest landscapes and some of their key characteristics. Such an approach seeks to conserve most of the biological diversity. Fine-filter strategies are implemented through stand-level management or conservation to protect rare species or those having particular and known habitat requirements. The hierarchy of coarse- and fine-filter approaches explicitly acknowledges that stand-level actions affect the landscape over time, altering characteristics such as forest composition and age structure. Finally, to ensure that objectives set under a FEM system are achieved, monitoring is crucial for assessing the implemented management system's success or failure and measuring the responses of target organisms to management (Drapeau et al., 2009). The results from this monitoring should then feed into future refinements, and new scientific knowledge should be incorporated through an adaptive management framework.

Retention forestry This forest management approach is based on retaining structures and organisms, such as living and dead trees and small areas of intact forest, both for harvesting and the longer term. Retention forestry aims to achieve temporal and spatial continuity in forest structure, composition, and the processes that promote biodiversity and sustain ecological functions at different spatial scales (Gustafsson et al., 2012). Retention is applied at various levels, from very low levels (Kuuluvainen et al., 2019) to up to 40% of the standing stock (Beese et al., 2019; Montoro Girona et al., 2019; Scott et al., 2019).

Continuous-cover forestry Continuous-cover management involves managing a forest without the use of clear-cutting. Harvesting is typically based on a single tree or group selection, and a significant portion of canopy trees is retained (Felton et al., 2016; Kim et al., 2021; Sharma et al., 2016; Sténs et al., 2019). This produces forests having an uneven-aged structure.

Restorative management Restorative management prioritizes ecological restoration while simultaneously harvesting for profit. This management approach represents the first step toward forest ecosystem management in regions where intensive forest management has decreased or has degraded biodiversity and ecosystem functions (Vanha-Majamaa et al., 2007).

Zoning approach (TRIAD) The TRIAD zoning approach, proposed by Seymour and Hunter (1992), has forested landscapes divided into three zones, each subjected to different management objectives (Burton, 1995; Nitschke & Innes, 2005). The reserve portion is devoted to conservation purposes, whereas the intensive management portion focuses on timber production and can potentially compensate for the lower timber yields because of the presence of conservation areas. Between these two endmembers of the production/conservation spectrum lies a multiple-use zone where extensive management is conducted. Management in this area does not focus solely on timber production but also includes maintaining some important elements for biodiversity (Montigny & MacLean, 2006). The overall objective is to sustain the forest to support the needs of society (Seymour & Hunter, 1999). The actual size of the respective zones is specific to each landscape (Burton, 1995; Harvey et al., 2009). For instance, if maintaining old growth is not possible or too expensive, more area can be preserved.

Intensive forest management (IFM) IFM aims to increase or maximize the value, volume, or both of desired forest components, often timber. Attaining this goal involves such practices as density regulation, regeneration control, silvicultural intervention, and genetic improvement (Bell et al., 2000). Silviculture applied to reach these goals focuses on practices designed to accelerate stand development and improve stand value and yield: site preparation, the planting of species matched to site conditions, and vegetation management timed to maximize early growth. IFM can include natural regeneration but with density regulation. It often requires a series of actions during the rotation to achieve growth and yield objectives (Bell et al., 2000). Sweden and Finland have implemented this approach successfully for almost all their managed forests. Although increasing productivity is the main goal of intensive forest management, it can also be done in the context of maintaining or restoring diversity.

Extensive forest management (EFM) EFM is a management approach that does not rely on a series of interventions to attain growth and yield objectives. Instead, it focuses on protecting the forest from the primary natural disturbances, such as fire and insects, and relies partly on natural regeneration to provide the next forest. Silvicultural interventions focus mainly on attaining a minimum density with desired species composition and maintaining a given age-class distribution (Bell et al., 2000). This form of forest management is used in large areas of Canada and Russia.

Conservation area (adapted from the IUCN glossary) These are areas of various sizes (from the stand to the landscape scale) dedicated to protecting, caring, managing, and maintaining ecosystems, habitats, wildlife species, and populations. The creation of these spaces aims to safeguard natural conditions for their long-term preservation by conserving ecosystems and natural habitats and maintaining viable populations of species.

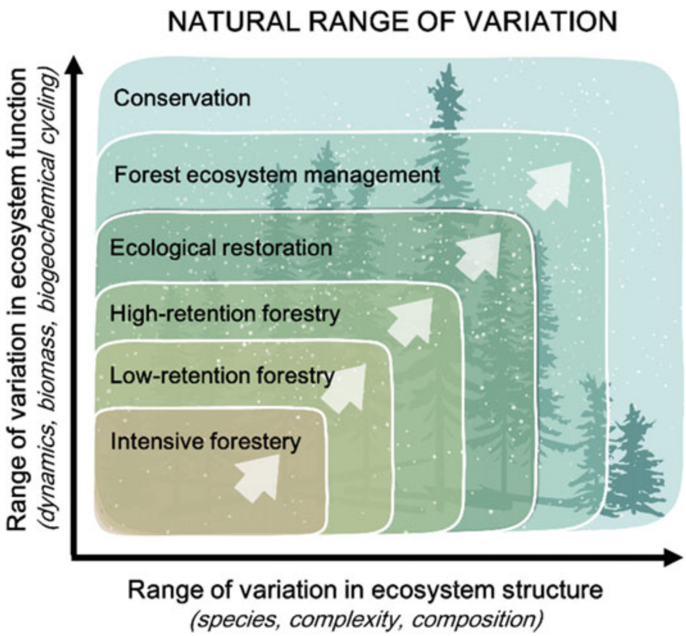

Fig. 1.2 The natural range of variability (NRV) is a means of framing or implementing sustainable forest management (SFM). Management approaches can be schematized in a conceptual hierarchy, in terms of species composition and ecosystem structure, in relation to their degree of overlap with NRV. Overlap is lowest for intensive plantation-type management but increases with retention forestry and ecological restoration; the latter is required in cases where the forest has been degraded by long-term intensive management or other uses (e.g., mining). Different management types can be combined within the same forest management unit. For instance, the TRIAD zoning approach (Messier et al., 2009), in which intensive management can increase the yield per hectare in some portions of the landscape, can be applied to decrease timber production pressure on other portions of the forest where extensive forest management is applied. Under the TRIAD approach, intensive and extensive management zones—along with conservation areas—are all included in the landscape in varying proportions, with each contributing to meet the goals of FEM

1.2 A Brief History of Boreal Forest Management Paradigms

1.2.1 The Early Era of Forest Management

Despite the extensive geographic spread of the boreal forest across the Northern Hemisphere, numerous commonalities exist among the ecological and management challenges for boreal countries. The main harvesting methods (clear-cutting) and silvicultural practices (single-cohort management, site preparation, planting, stand tending) are similar throughout the circumboreal forest. Common issues related to this management approach include landscape fragmentation, the loss of mature and old-growth forests, the homogenization of forest structure and tree species composition, and forest susceptibility to the impacts of climate change. However, boreal countries also differ in their forest exploitation histories and their forest management cultures, policies, and priorities. When evaluating the current situation and challenges, it is essential to consider the respective forest management histories (See Chap. 31). Here, we briefly describe the historical background and development of forest management in Canada, Sweden and Finland, and Russia.

1.2.2 Canada

In Canada, boreal landscapes were and remain inhabited by First Nations. Traditional Indigenous livelihood relies on forest resources for hunting, trapping, gathering, and various provisioning and cultural services (Chap. 20). Traditional land management is based on deep ecological knowledge and aims to maintain the capacity of the land to sustain life (Feit, 2001). For instance, fire was used in some regions of boreal Canada until the 1950s to maintain blueberry patches, attract wildlife within strategic areas, and prepare the soil for planting (e.g., Berkes & Davidson-Hunt, 2006; Lewis & Ferguson, 1988). The transition to commercial forestry has, however, restricted the forest management role of First Nations.

Large-scale commercial harvesting of forests began in the early nineteenth century, focusing on conifer species used for construction, firewood, and shipbuilding (Drushka, 2003; Gaudreau, 1998). During the nineteenth century, Canadian forestry entered its administrative period, responding to the need for a regulatory approach to better preserve timber supplies and safeguard the stability of the forest industry. By the end of the century, most provincial jurisdictions had adopted forestry policies, thereby establishing the first forest management regimes, which now form the basis of current policies. The Canadian Forest Service, a federal research agency, was established in 1899, and the University of Toronto inaugurated the first forestry school in Canada in 1907. Moreover, between 1871 and 1921, 11 treaties were signed between the Crown and First Nations to open the land for settlement in the south and secure access to natural resources in the north (Crown–Indigenous Relations and Northern Affairs Canada, 2020).

An impending decline in timber capital in Canada first became apparent at the onset of the twentieth century; this precipitated a transition to the era of *sustained yield forest management* (see Box 1.1; Bouthillier, 1998; Canadian Forest Service, 1998; Drushka, 2003). This management approach, also called *fully regulated forest*, involves compartmentally managing for an even forest age-class distribution, which theoretically ensures a regular and constant supply of similar wood volume over time. In the boreal forest, sustained yield forestry developed under an even-aged management system, using primarily clear-cutting and controlling forest age structure via management units. Under this system, forests are scheduled for harvest when volume increase levels off (maximum mean annual increment); this corresponds to a stand age of 50 to 150 years, depending on the forest type and location (Duchesne, 1994; Stadt et al., 2014).

This stand-wise even-aged management approach emphasized *normalizing* the boreal forest stand age distribution by the targeted harvesting of *overmature* stands, considered less productive. This approach also aimed for the long-term sustainability of timber supply by ensuring that annual harvests did not exceed what the forest produced. Thus, sustained yield management aimed to harvest a regular amount of timber and ensure the preservation of the forest capital. Nonetheless, in Canada, with its vast expanses of unmanaged forest, forestry has been mostly extensive since the Second World War.

Forest management is more intensive in Sweden and Finland and has a longer history relative to the Canadian context. Although clear-cutting and planting are common in both regions, Canadian forest management places greater reliance on natural regeneration and less use of intensive management approaches, such as early stand tending, fertilization, and thinning. In many regions of Canada, the forest industry continues to rely exclusively on primary forests, which have not been previously subjected to organized forest management.

1.2.3 Sweden and Finland

In this vast geographic area, and more recently in its northern parts, the Indigenous Sami people were among the first forest dwellers and users. Although their population size was relatively small, their mobile reindeer herding culture impacted forests (Josefsson et al., 2009). Since the Middle Ages, the regional human population has increased, and the boreal forest has been used for diverse purposes. Major influences include charcoal production for the large-scale mining industry (especially in Sweden), shipbuilding, tar production, and slash-and-burn agriculture (especially in Finland). Other extensive and important uses of the forest included domestic-use cuttings for firewood and building material as well as cattle herding in forests surrounding settlements.

Multiple impacts due to selective cutting, the careless use of fire, and cattle herding in forests prevented forest regeneration, leading to the regional scarcity or even depletion of timber by the nineteenth century. This development sparked fears of a permanent loss of these forests (Keto-Tokoi & Kuuluvainen, 2014; Östlund et al., 1997). At the same time, the *timber frontier* moved north along rivers in search of pristine forests and timber that could be floated to sawmills on the coast (Östlund & Norstedt, 2021).

The local and regional depletion of forest resources, combined with increased demands for wood as the forest industry expanded after the mid-nineteenth century, culminated in the need to organize forestry more effectively in terms of regulations, administration, and the education of forest managers. Sweden established a forestry institute in Stockholm in 1828 to train forestry professionals (Puettmann et al., 2009). In Finland, the Evo forestry school began to educate professional foresters in 1858. Legislation was also established to halt the careless use of forests. In Finland, for example, the 1928 Law on Private Forests by and large outlawed clear-cutting, allowing this practice only for special reasons. In the late-1940s, however, the interpretation of the law took a 180° shift; selective logging was outlawed, and only clear-cutting coupled with subsequent regeneration was allowed.

This development was linked to the establishment of the pulp and paper industry after the Second World War when smaller and lower quality timber also became merchantable. This change, coupled with low-cost fossil fuels and advances in harvesting technologies, led to a large-scale transition from selective harvesting to clear-cutting and even-aged forest management (Östlund et al., 1997; Siiskonen, 2007). At the same time, government-directed public funds into forestry infrastructure, such as building road networks and improving forest regeneration techniques and silvicultural practices.

In Finland, the large-scale ditching of forested peatlands was initiated to increase forest growth and raw material supply for the forest industry in the future (Keto-Tokoi & Kuuluvainen, 2014). The post–Second World War economic and construction boom led to the large-scale clear-cutting of natural or near-natural forest in both Sweden and Finland. As part of the terms of the peace treaty, Finland had to pay reparations to the Soviet Union and forest industry products formed part of this compensation, further increasing the extensive clear-cutting of natural and near-natural forest, especially in northern Finland, in the late 1940s and 1950s. Strict national laws and forest policies drove the development of forestry practices. Still, there was strong opposition among private forest owners, who had selectively harvested their forests for decades.

In both Sweden and Finland, the most significant change in forest utilization and management occurred when the formerly dominant selective cutting practices were rejected and even-aged management driven by clear-cut harvesting and regeneration by planting or seeding became the dominant method. This management model was favorable for the influential and economically important pulp and paper industry and hence formed a key part of the national forest policies, where increasing timber yield was the primary goal.

1.2.4 Russia

Historically, human-forest interactions in boreal Russia were minimal owing to the lack of roads and the sparse human population scattered across the vast expanses of forest. Northwestern Russia was an exception to this pattern, as forests were closer to settlements. Since the fifteenth century, human activities in the boreal forest of this region have included slash-and-burn cultivation, the use of wood for buildings and heating, and the production of tar, potash, salt, and charcoal for industry. The first legislation related to forest harvesting dates from the early eighteenth century when large-diameter trees along rivers were required to supply Peter the Great's shipbuilding program (Fedorchuk et al., 2005; Redko, 1981; Sokolov, 2006). The first forestry university in Russia was established in 1803 in St. Petersburg.

Over the last centuries, forest management in Russia has been closely linked to the country's dramatic political and economic changes. Whereas traditional forestry in Russia had obvious German roots, the second half of the nineteenth century and the beginning of the twentieth century were periods of rapid development of national forest science and increased study of natural forest ecosystems, forest management, and silviculture (Morozov, 1924; Orlov, 1927, 1928a, b). At the onset of the First World War, however, only 5% of Russian forests had been inventoried and had developed forest management plans; another 13% had been surveyed for different goals (Kozlovsky, 1959). The 1923 Forest Code acknowledged various functions of forests (protection, conservation, cultural and commercial uses) and formed the basis for further classification of forests into major functional forest management categories.

Around 1930, extensive management began to restore and industrialize the economy, normalizing the harvest of the most productive and accessible stands, the preferential selection of the most valuable tree size and quality, and the use of natural and assisted regeneration (Fedorchuk et al., 2005). Typical forestry involved large-scale "concentrated" clear-felling with 50–100 ha harvesting areas and, in many cases, substantially larger surfaces (Aksenov et al., 1999; Fedorchuk et al., 2005; Kozubov & Taskaev, 2000) until the second half of the 1960s, whereas other features of extensive forest management remain in application (Sokolov, 2006). These concentrated harvesting areas were not conventional clear-cuts, as foresters left behind large uncut patches of various sizes and individual trees of unused species or individual trees having bad stem quality (Baranov, 1954; Solntsev, 1950). Moreover, in the *incomplete clear fellings*, 61–90% of the stand growing stock was harvested (Melekhov, 1966), representing a retention level of up to 40%. This model, however, decreased the growing stock or altered stand composition over large areas in the managed parts of the boreal zone. These changes, combined with large fires in post-harvesting areas, encouraged the logging of new previously uncut regions in Russia.

1.3 New Forest Paradigm After Sustained Yield Management

Intensive even-aged forest management and the sustained yield approach have provided a sustained supply of wood fiber for industry, as reflected by the success of Sweden and Finland in increasing forest yield. Toward the end of the twentieth century, throughout the boreal biome, the cumulative adverse ecological effects of even-aged management with clear-cut harvesting began to draw attention (Franklin, 1989). These negative consequences include the simplification of forest structures, the disappearance of old, large trees, and the decline in the amount of deadwood (Chap. 5). Sustained yield management based on the "fully regulated forest" paradigm began to be questioned for its inability to maintain forest values and resources other than timber.

Short harvest rotations with clear-cutting were shown to fundamentally alter ecosystem structure compared with conditions produced through natural disturbances; the latter are more variable in terms of frequency, severity, and extent than traditional harvesting approaches. Particular concern involved managed forest landscapes becoming fragmented because of the loss of older and more structurally heterogeneous forests, which dominate landscapes under longer, or less severe, natural disturbance regimes (Cyr et al., 2009; Franklin, 1997; Kuuluvainen, 2009; Östlund et al., 1997). Most managed boreal forest stands suffered declines in deadwood, reduced structural heterogeneity, and, in some cases, tree species diversity (Chap. 6; Shorohova et al., 2019; Siitonen, 2001). In many regions, young, structurally homogeneous stands with early successional species began to dominate managed forest landscapes. This change was accompanied by a reduction in the area hosting older, structurally complex stands dominated by later successional species and large living and dead trees (Cyr et al., 2009; Kuuluvainen & Gauthier, 2018; Shvidenko & Nilsson, 1996).

These concerns were accompanied by a growing scientific knowledge related to (1) the relationships between forest structure, stand age, and biodiversity; (2) the importance of biological legacies in forest regeneration and succession; (3) the critical role of deadwood in forest ecosystem functioning and biodiversity; (4) the importance of natural disturbances as key ecological drivers within forest landscapes; and (5) the relationship between biodiversity and forest productivity, resistance, and resilience (Angelstam, 1998; Bergeron & Fenton, 2012; Bergeron et al., 2017a, b; Burton, 2013; D'Amato et al., 2017; Franklin, 1997; Gauthier et al., 2009; Gustafsson & Perhans, 2010; Lavoie et al., 2019; Montoro Girona et al., 2016).

Together with increased public and market awareness of the importance of sustaining the economic, ecological, and social/cultural values of forests, these concerns led to the emergence of a new forest management paradigm. The term *sustainable forest management* (SFM) was coined in the "Forest Principles" arising from the United Nations Conference on the Environment and Development (UNCED; i.e., the Rio Earth Summit) in 1992. In the subsequent years, countries collaborated to define SFM criteria and indicators (Wilkie et al., 2003). At the Conference of the Parties of the Convention on Biological Diversity (CBD) held in Jakarta in 1995, participants identified the *ecosystem approach* (EA)—an integrated strategy for conserving and sustaining land, water, and biological resources—as the primary framework for actions under CBD (Box 1.2). Both approaches have been very influential in developing forest ecosystem management in the boreal biome.

The fundamental difference between FEM and traditional forest management lies in the former's focus on managing the forest as an integrated, holistic, ecological entity existing at multiple spatial and temporal scales. FEM explicitly incorporates planning for what is to be extracted and for the full range of economic, ecological, and social/cultural values to be maintained within the landscape. Thus, this approach considers not only forest structure and composition but also ecological processes such as biogeochemical cycling, forest regeneration, species migration patterns, carbon sequestration, and ecosystem resistance and resilience (Gauthier et al., 2009; Palik et al., 2020). Although the definition of the concepts and practical applications vary from one jurisdiction to another, common principles, characteristics, and goals are shared among most national frameworks (see Box 1.2; Christensen et al., 1996; Galindo-Leal & Bunnell, 1995; Gauthier et al., 2009; Grumbine, 1994; Kimmins, 2004).

Box 1.2 Origins of the Sustainable Forest Management/Ecosystem Approach

The "Forest Principles" arising from the United Nations Conference on the Environment and Development (UNCED, i.e., the Rio Earth Summit) in 1992 helped define the concept of sustainable forest management (SFM), which was subsequently adhered to and developed by many countries. Conceptually, SFM aims to balance the ecological, economic, and sociocultural pillars of forest management. The goal of SFM is to provide integrated benefits to all, including safeguarding local livelihoods, protecting biodiversity and other ecological services provided by forests, reducing rural poverty, and mitigating some of the effects of climate change. Despite variations in definitions among countries, several criteria serve as common targets for SFM. These include: (1) the maintenance of the extent of forest resources; (2) the conservation of biological diversity (genetic, species, landscapes); (3) the conservation/enhancement of forest health and vitality; (4) the maintenance of forest productivity; (5) the maintenance of the ecological functions of forests, such as water cycling, carbon cycling, and interactions with climate; (6) the maintenance of socioeconomic benefits from forest resources.

At the Conference of the Parties of the Convention on Biological Diversity (CBD, 1995), the ecosystem approach (EA) was proposed as a framework for conserving biodiversity and ensuring the sustainable use of ecosystem resources. Its development continued until 2000 with the framing of an integrated strategy for conserving and sustaining land, water, and biological resources (Wilkie et al., 2003). The CBD (2000) defines EA as:

> a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. [EA is] based on the application of appropriate scientific methodologies focused on levels of biological organization, which encompass the essential structure, processes, functions and interactions among organisms and their environment. It recognizes that humans, with their cultural diversity, are an integral part of many ecosystems.

Several principles of EA are similar to those proposed in SFM, whereas other principles focus more on ecosystem complexity and functioning. Important elements are that EA should: (1) consider management effects on adjacent ecosystems; (2) prioritize the maintenance of ecosystem structure and function; (3) manage the ecosystem at appropriate temporal and spatial scales relevant to long-term management objectives; (4) establish a balance between conservation and the use of biodiversity; and (5) consider all forms of information be it scientific, traditional ecological knowledge (TEK), etc. "…overall, SFM and EA express similar goals and ambitions for forest management focussing on environmental, social and economic sustainability, and on generating and maintaining benefits for both present and future generations." (Wilkie et al., 2003). In Canada, the Canadian Council of Forest Ministers adopted the SFM principles in 1995 (CCFM, 1995).

1.4 Implementing Sustainable Forest Management Within Boreal Regions: Approaches, Successes, and Shortfalls

Over the past three to four decades, boreal jurisdictions have agreed to the SFM principles and have more or less succeeded in implementing FEM within forestry policies, regulations, and planning.

1.4.1 Canada

In North America, both SFM and FEM emerged out of the ideas of ecological forestry of the Harvard Forest developed in the 1940s (D'Amato et al., 2017). These ideas were modified further and became known as *new forestry* or NDBM (Franklin, 1989; Gauthier et al., 2009; Hunter, 1993). These concepts have since been implemented partly (the late 1990s) by forest managers by fitting these approaches into traditional planning schemes of forest management (Box 1.1; Harvey et al., 2003).

Since the 1990s, the implementation of FEM in the boreal forest of Canada has been deeply rooted in an understanding of past disturbance regimes (NDBM) and the natural range of variability (NRV; Box 1.1) of these events (Gauthier et al., 2009; Ontario Ministry of Natural Resources, 2001; Perera et al., 2004). This was considered a precautionary coarse-filter approach, as without a proper understanding of ecological mechanisms, maintaining natural forest conditions within the NRV was perceived as a suitable means of preserving the ecological structure, function, and resilience in forested landscapes (Cissel et al., 1999; Hunter, 1993). The NRV concept aims to maintain the characteristics of managed stands and landscapes within the historical natural range of variability (Cissel et al., 1999; Landres et al., 1999). Although the implementation of FEM has differed among Canadian jurisdictions, commonalities have emerged. These similar ideas are notably because of the existence of the NSERC (Natural Sciences and Engineering Research Council) *Sustainable Forest Management network* (SFMn), a large research–industry partnership, which existed between 1995 and 2010 (https://sfmn.ualberta.ca/about-us/ consulted 26 April 2021).

One of the FEM framework elements aimed to facilitate "the formulation of environmental issues and the development of targets that have to be sustained or achieved within the implemented management system" (Gauthier et al., 2009). With the transition toward FEM, several attributes and processes manipulated by forest management were identified as vulnerable because of past management approaches. It was also recognized that long-term planning over large areas was needed to ensure the maintenance or restoration of these attributes (Table 1.1). These identified attributes included (1) the proportion of different forest age classes (old-growth versus young forest) and their spatial distribution across the landscape; (2) the landscape pattern of forest composition at the stand and landscape levels and associated dynamics; (3) variable internal stand structure; the retention of biological legacies such as deadwood or the pit and mound aspects of soils; (4) soil fertility and site productivity (Gauthier et al., 2009). The fire regime was the main disturbance regime on which the FEM was based in Canada (Bergeron et al., 1999, 2002; Ontario Ministry of Natural Resources, 2001; Vaillancourt et al., 2009). More recently, low and moderate severity disturbances (wind, insect, and low severity fire) have been recognized as contributing to NRV and have been slowly incorporated into FEM (Chap. 4; Bergeron et al., 2017a, b; De Grandpré et al., 2018; Lavoie et al., 2021; Stockdale et al., 2016). For instance, it is now recognized that although both fire and insect outbreaks over the Holocene have co-occurred at a regional level, outbreaks were more frequent when fire frequency was low (Chap. 2; Navarro et al., 2018b). These disturbances also strongly influence forest dynamics, impacting the amount, composition, and structure of old forests (Martin et al., 2019, 2020). In short, the characterization of the range of variability in past disturbance return intervals, severity, and extent over the last few centuries serves to set targets for maintaining or recovering particular forest characteristics, e.g., successional stages (old forest), forest composition (shade-tolerant species), and forest structure (Table 1.1; Chap.7).

Several experimental studies examining the effects of partial harvesting and variable retention have been established in various regions of Canada (Chap. 16; Box 1.1; Brais et al., 2004; Fenton et al., 2013; Montoro Girona et al., 2016; Ruel et al., 2007; Spence et al., 1999), and the knowledge gained from these research projects has slowly been implemented into operational practice. Assessment of the impacts of these treatments on biodiversity, forest regeneration and dynamics, deadwood dynamics, soils, and carbon storage (for up to approximately 15 years post-harvest) has provided considerable insight into the ecological structure, functioning, and dynamics of these forests. Retention or partial harvesting has been shown as a means of meeting FEM objectives (e.g., Bartels et al., 2018; Fenton et al., 2013; Franklin et al., 2018; Montoro Girona et al., 2016, 2017, 2018a, 2019; Moussaoui et al., 2020; Pinzon et al., 2016; Thorpe & Thomas, 2007; Work et al., 2010). The results are

Table 1.1 Natural disturbance–based management (NDBM)/natural range of variation (NRV) targets for addressing sustainable forest management (SFM) issues identified at the end of the 1990s (Gauthier et al., 2009) for which a FEM framework would help achieve. Current implementation approaches for different regions of the circumboreal forest are also presented

NDBM/NRV targets to address the issues	SFM issues and potential effects	Application in management in different regions of the boreal forest			
		Eastern Canada (Québec)	Western Canada (Alberta)	Sweden–Finland	Russia
Maintain the age-class structure within the observed and past NRV	Decrease in mature and old forest	Age-class structure designed to maintain some (minimal) quantities of old forest (on the basis of NRV) and to avoid exceeding a certain level of young forest	Rotation length designed to match natural disturbance rates	No NRV-based targets; fully regulated forest age-class structure on the basis of clear-cut rotation	Maintain the age-class structure (even-aged vs. uneven-aged forest; all age classes) to approach a quasi-normal age-class distribution
	Increase in young forest		Targets for areas in different age classes within regions	Some continuous-cover management	
			Requirement to maintain some areas without human intervention		

(continued)

Table 1.1 (continued)

NDBM/NRV targets to address the issues	SFM issues and potential effects	Application in management in different regions of the boreal forest			
		Eastern Canada (Québec)	Western Canada (Alberta)	Sweden–Finland	Russia
Maintain forest composition within the past NRV (sometimes based on knowledge of fire cycles)	Increase of shade-intolerant species	Experimental use of mixed silviculture (SAFE, etc.)	Requirement to regenerate with species harvested	No NRV-based targets; deciduous tree species mixture is promoted in forest regeneration in all site types	Natural regeneration after clear-felling; the share of pioneer shade-intolerant species remains high
	Decrease of old-growth species	Some operational mixed-species plantations	Some efforts to regenerate to mixedwood stands and regulations to facilitate regeneration	Some continuous-cover management	To protect old-growth species, there are no forestry activities in reserves and clear-cutting is forbidden in protected forests
	Homogenization of stand composition	Adjustment of silviculture scenarios (education)	Alternative silviculture approaches to maintain mixedwoods (e.g., understory retention, underplanting)	Old-forest protection; preserving key biotopes and leaving retention trees on clear-cuts	Selection felling systems
		Extended rotations or partial cuts where long-lived species are present; silvicultural actions to maintain or ensure regeneration			Preserving key biotopes in all categories of forest
					Smaller sizes of harvested areas
					Mixed silvicultural systems; Assisting natural regeneration with planting under the tree canopy and/or after harvesting

(continued)

Table 1.1 (continued)

NDBM/NRV targets to address the issues	SFM issues and potential effects	Application in management in different regions of the boreal forest			
		Eastern Canada (Québec)	Western Canada (Alberta)	Sweden–Finland	Russia
Emulation of fire-size distribution (young forest) and distances among large forest tracts	Change in connectivity within and between open and closed stands	Some emulation of the size and shape of young forest and residual patches resulting from fire	Some emulation of the size and shape of patches resulting from wildfires	No NRV-based emulation of fire-size distribution	Spatial landscape planning
					Forest monitoring, improvement of disturbance management strategies (e.g., fire and large-scale insect outbreaks)
	Fragmentation of forest landscapes and loss of old-growth stands	Minimum amount of large forest tracts to be maintained (massifs)	Requirement to maintain areas of a certain size without human disturbance to support interior- and old-growth-dependent species (e.g., woodland caribou)	Landscape ecological planning in state and company lands; forest protection based on spatial optimization	Preserving key biotopes and ecotones (e.g., between forest and peatlands)
	Rate of cumulative disturbances exceeding the capacity of the stand/landscape	Some consideration of fire and insect disturbances in annual allowable cut computation	Some consideration of fire and insect disturbances in annual allowable cut computation	Cuttings mostly in line with sustainable yield limits; concerns about cumulative impacts on ecological sustainability (biodiversity)	Conservation of intact forest landscapes
			Consideration of the total disturbance footprint in an area (e.g., oil & gas and forestry) through the biodiversity management framework		Introduction of special forest management regimes in landscapes containing stands of old-growth forest

(continued)

Table 1.1 (continued)

NDBM/NRV targets to address the issues	SFM issues and potential effects	Application in management in different regions of the boreal forest			
		Eastern Canada (Québec)	Western Canada (Alberta)	Sweden–Finland	Russia
Emulation of stand structure on the basis of forest dynamics and disturbance regime severity	Decreases in uneven-aged forest and complex stand structure	Experimental partial cuttings	Requirement to leave some areas uncut (e.g., riparian buffers, key wildlife habitat) and leave a minimum amount of green-tree retention within harvest blocks	Leaving retention trees, preserving key biotopes, continuous-cover management	Retaining unharvested patches within harvested areas and on their edges
	Decreases in deadwood quantity and quality	Extended rotations	Retention harvesting; avoidance of harvesting in key wildlife habitat	Leaving small amounts of retention trees, protecting deadwood in harvesting operations, protecting key biotopes	Seed trees are, in most cases, left permanently
	Loss of ecological attributes specific to naturally disturbed stands due to suppression or salvage logging	Green-tree retention of various forms and amounts in some of clear-cuts Guidelines to leave disturbed areas (1/3) of various severity untouched after any fire event	Unburned patches and some burned forest left during salvage logging; some insect-disturbed areas left unsalvaged	Some prescribed and restoration burnings, retention trees, protection of key biotopes	Almost all deadwood is left on harvested areas

(continued)

Table 1.1 (continued)

NDBM/NRV targets to address the issues	SFM issues and potential effects	Application in management in different regions of the boreal forest			
		Eastern Canada (Québec)	Western Canada (Alberta)	Sweden–Finland	Russia
Maintain site regenerative capacity and productivity	Poor regeneration or growth leading to low density, unproductive stands	Soil scarification on paludified sites	Replanting of conifers	Soil scarification, protection of undergrowth in harvesting	Preserving undergrowth during harvesting
		Some plantations or enrichment plantings	Regeneration surveys to quantify the growth of regenerated stands		Tending natural regeneration and complemented by planting, if not successful
			Standards for minimum density and spacing in regenerated stands		
	Decline in soil fertility	Obligation to leave branches and leaves on poor sites	Fine slash often left on site	Soil scarification, prescribed burning, maintenance of deciduous mixtures	All logging slash is left

slowly being applied to operational harvesting, forest management planning, and government policy (Jetté et al., 2013; Ontario Ministry of Natural Resources, 2001).

Despite the push for implementing a FEM framework, several elements of this paradigm remain unaddressed, and not all elements of the framework have been implemented (Table 1.1; Van Damme et al., 2014). In some Canadian jurisdictions, targets exist for maintaining a minimal proportion of forest older than a certain age, and some constraints have been produced related to the acceptable amount of young forest within various land units (Table 1.1; Alberta Sustainable Resource Development, 2006; Bergeron et al. 2017a, b; Bouchard et al., 2015; Jetté et al., 2013). Elsewhere, harvesting rotation cycles are designed to be aligned with the mean average fire return interval of the regional forest (DeLong, 2007).

Some Canadian jurisdictions have developed requirements to regenerate stands having the same composition as the original harvested forest. These requirements include efforts to regenerate mixedwood stands (Alberta; see Table 1.1). Retention harvesting (Box 1.1) is adopted increasingly to maintain stand structural heterogeneity, deadwood amounts, and key habitat features such as old, large trees. Maintaining forest productivity is approached through strict requirements for regenerating to sufficient density and monitoring to ensure early stand growth (Québec, Alberta; see Table 1.1). In some areas, there are considerations to maintain mixed stands, although true mixedwood management is uncommon (Chap. 15). In terms of spatial configuration, the shape and size of cutblocks have been modified in many instances to emulate the patterns created by natural fires (Ontario Ministry of Natural Resources, 2001). The conservation of key species is approached by conserving key habitats and maintaining some larger areas lacking human disturbance. Efforts are also undertaken to maintain the within-stand structure through partial cutting and tree retention (Table 1.1).

Although some FEM elements based on the NDBM/NRV approach have been applied, FEM has yet to be fully implemented. For example, despite both the importance of preserving old forests or forests with recognized old-growth attributes and the recorded increase in green-tree retention harvesting, forest management continues to operate predominantly under a single cohort, even-aged management system with low-retention clear-cut harvesting and short rotation cycles. This system tends to reduce the proportion of older forest stands while homogenizing the forest structure (Bergeron et al., 2006; Bouchard & Garet, 2014; Dhital et al., 2015). Stand-level considerations remain largely the focus of planning and management processes, and the focus continues to lie mostly on structures to a much greater degree than on processes. Moreover, although there is recognition of the importance of monitoring the effects of silviculture and management practices to determine whether the objectives for biodiversity and forest productivity have been achieved, this has only been partially fulfilled in operational landscapes (Chap. 14).

The consideration of First Nations values and rights in forest management is developing through various mechanisms in Canada. Co-management initiatives were launched through Canada's Model Forest program (1992–2007) (Bullock et al., 2017). The program aimed to define and implement sustainable forest management at the local and operational scales through a collaborative exercise (Bullock et al., 2017). The program generated an important research effort in both the natural and social sciences (Bonnell, 2012) and led to some lasting partnerships; for example, the Prince Albert Model Forest, inaugurated in 1992, is co-managed by a group of stakeholders, including First Nations, federal and provincial agencies, research agencies, and industry (Bouman et al., 1996). Its success is attributed to the implication of First Nations at all levels of governance.

The signing of modern treaties and agreements between First Nations and levels of government provides another mechanism. The *James Bay and Northern Québec Agreement* was the first modern treaty in Canada (1975). The treaty led to *La Paix des Braves Agreement*, negotiated between the Grand Council of the Cree (*Eeyou Istchee*) and the Québec Government in 2002. The forestry chapter's spirit enhanced the importance of the Cree traditional lifestyle, sustainable development, and the consultation process within Eeyou Istchee, the land of the Cree. This treaty initiated the monitoring and regulation of timber harvesting at the trapline scale, per local land use and management. It also officialized the roles and responsibilities of the tallyman, often a family elder, as the trapline manager (Whiteman, 2004). Despite some successes, many challenges remain for considering First Nations values and rights in forest management. They include the conciliation of values and knowledge (Asselin, 2015), the consideration of Indigenous land use in forest planning and monitoring (Bélisle & Asselin, 2021; Bélisle et al., 2021; Saint-Arnaud et al., 2009), and the adaptation of governance structures for First Nations to be involved at all decision-making steps.

1.4.2 Sweden and Finland

In Sweden and Finland, the pathways toward FEM have differed from those of Canada. These differences between the chosen FEM approaches of both regions partly reflect conditions and restrictions determined by differences in forest-use histories and ownership structures. In Canada, boreal forests are primarily state-owned, and harvesting has, until now, involved mainly primary forests rented to forestry companies as long-term concessions; this organization facilitated the development of landscape-level coarse-filter management approaches. In Sweden and Finland, on the other hand, implementation was mainly fine-grained, reflecting the long history of intensive forest use, where pristine forests have largely disappeared, and most harvesting occurs within secondary or human-influenced—to varying degrees—forest. Moreover, the distribution of forest ownership among numerous private forest owners hampers the development of larger-scale approaches.

The first marked initiative was the introduction of the ASIO-model based on fire occurrense (Absent, Seldom, Infrequent, Often; Angelstam, 1998). This approach was based on the assumptions of natural fire regime effects on forest structure and dynamics (Angelstam, 1998; Kuuluvainen & Grenfell, 2012). Although influential as a pedagogical tool, the model's implementation in the field was only vaguely based on reference conditions. One problem was the lack of a proper understanding of natural fire ecology (Berglund & Kuuluvainen, 2021). Thus, instead of coarse-filter approaches, the focus mainly fell on biodiversity conservation by protecting ecologically valuable but relatively small-scale features, such as *woodland key habitats* (Timonen et al., 2010). Although the definition varies somewhat between countries, these are typically small—moist, fertile sites hosting high biodiversity and that are seldom naturally disturbed. Because they are small and sparsely located across the landscape, the ability of species to move between patches can be restricted; thus, the capacity of these patches to protect species populations from a metapopulation perspective has been questioned (Hanski, 2000).

Another approach to compensate for the adverse ecological impacts of clear-cut timber harvesting involves leaving retention trees during harvesting operations (Box 1.1; Gustafsson et al., 2012; Simonsson et al., 2015). However, the applied tree retention is typically low; for example, in Sweden–Finland, it is common to leave only a small number of trees (5–10 per ha) (Kuuluvainen et al., 2019). As the retention level strongly influences species responses, the low retention levels do not provide the habitat quality and continuity needed for declining and red-listed forest species, notably as many are dependent on old living trees and coarse woody debris. The accumulated research evidence suggests that current retention levels are too low to provide credible positive effects on biodiversity (Kim et al., 2021; Kuuluvainen et al., 2019).

Together, tree retention practices, protection of woodland key habitats, and conservation areas have been called the *hierarchical multiscale approach* to biodiversity conservation (Gustafsson & Perhans, 2010). However from the 1990s onward, the practices have been mainly fine-filter or *precision-conservation* approaches, which aim to protect valuable small-scale habitats and the associated biodiversity. In contrast, forest management has focused less on the large-scale ecosystem components, forest structures, and processes, i.e., the coarse-filter approach. Thus, actions related to biodiversity conservation are generally not part of any integrated ecosystem-based management framework but instead are implemented as separate measures on top of the intensive, business-as-usual even-aged management system (Kuuluvainen et al., 2019).

Research efforts to develop coarse-filter-inspired management based on natural disturbances have been put forward. An example is the DISTDYN project. This project involves an experimental setting specifically designed to emulate natural disturbance patterns in harvesting (Koivula et al., 2014). The focus is on large-scale (150–200 ha) blocks or "landscapes," each characterized by a different scale of harvesting units (from single tree selective cuts to clear-cutting) and retention level, derived from recent research on natural disturbance dynamics (Kuuluvainen & Aakala, 2011).

Despite the ongoing implementation of SFM strategies and practices, the managed forest landscapes in Sweden and Finland face considerable challenges. Biodiversity loss remains a serious concern, and habitat loss and fragmentation continue to drive the ecological degradation in boreal forests. In Sweden and Finland, the long history of intensive forest management for timber production has reduced habitat quality and connectivity. In Finland, for example, there are currently 816 endangered forest species (Hyvärinen et al., 2019), and the extinction debt of forest species because of forest management is estimated at around 1,000 species (Hyvärinen et al., 2019). This loss of biodiversity is likely to adversely affect the functioning of forest ecosystems (i.e., decomposition of organic matter, nutrient cycling, and carbon sequestration) and the capacity of forests to provide ecosystem services (Duffy, 2009). The main drivers of biodiversity decline are the loss of natural forest habitats, including those lost through wildfire (Bergeron & Fenton, 2012; Koivula & Vanha-Majamaa, 2020; Nordén et al., 2013). Growing concerns about biodiversity loss in Swedish–Finnish forests (Granström, 2001; Kouki et al., 2001; Hyvärinen et al. 2019) have heightened the importance of maintaining and even restoring biodiversity (Kuuluvainen, 2009). Although the last 20 years have been witness to several retention and restoration experiments (Halme et al., 2013; Koivula & Vanha-Majamaa, 2020; Vanha-Majamaa et al., 2007), the knowledge produced from these studies has yet to be implemented at a larger scale (Koivula & Vanha-Majamaa, 2020; Kuuluvainen et al., 2019).

1.4.3 Russia

Russia took a different path in implementing SFM because of the significant sociopolitical changes of the past 50 years. The Soviet period of forest management left a diverse legacy. On the one hand, the Soviet system produced a well-developed forest science and professional education structure. It established sound systems of forest inventory and management, forest regeneration, and protection against disturbances. Forests also had a relatively high political profile for some periods, such as during Stalin's plan of nature transformation (1948–1953) (Koldanov, 1992), and the Soviet system improved our understanding of the role of forests in a changing world. On the other hand, the Soviet political and economic system was incapable of generating a forest strategy able to address the challenges of a rapidly changing world. Political pressure, inappropriate forest statistics, misleading information about the availability of forest resources, and ignored regional natural and sociocultural variation in forest structure and functions hampered the development of state forest policy.

The dramatic political, social, and economic changes in Russia after the 1990s worsened the situation with the reforms introduced by the Forest Code published in 2006. Currently, forests in Russia are owned by the state and are leased to private forest companies. Forest management is regulated by the Forest Code of 2006—although many subsequent corrections have been made—and numerous federal and regional laws and regulations. The practice of forest leases does not, however, correspond to sustainable forest management principles. As a result, the governance and protection of forests have deteriorated significantly. Areas in which major silvicultural treatments have been implemented have decreased two to four times relative to areas in the 1990s (FAO, 2012; Petrov, 2013; Shvidenko et al., 2017; Shutov, 2006). In some jurisdictions, the amount of available timber resources has become depleted. There are currently intense debates on these issues within Russian industry, government, and academia.

Russia is a member of both the Montréal and pan-European processes on criteria and indicators for sustainable forest management. Most boreal forests used for wood production are certified according to national Forest Stewardship Council (FSC) standards (Elbakidze et al., 2011). Although some appropriate decisions have been made, none of the top-level decisions during the last three decades have been fulfilled completely.

All Russian forests are divided into protective, commercial (exploitable), and reserve forests. Protective forests are divided into four categories, each having different management regimes—from the complete prohibition of any harvest to varying levels of restriction—and aim to protect natural areas as well as water supply and quality through providing protective belts of forest along transport ways or in cities, forest parks, urban forests, and other valued forests, e.g., anti-erosion forests, forests growing in steppe, forest–tundra, and high mountains. Most of the forest estate lies within the commercial category. The forest inventory data estimates this area at approximately 40% of the total boreal forest area within the country. Diverse categories of protective forests comprise 26% of the total forest area. Reserve forests are practically unmanaged territories (around 210 million ha in 2010), as they are not planned to be harvested within at least the next 20 years.

Since 1978, in addition to the particular state-level protected areas, key biotopes (forests of 0.1–1,000 ha), which can occur in protective, commercial, and reserve forests, remain partly or entirely unmanaged; for example, habitats of rare species or old-growth forests are completely unmanaged. Clear-felling is forbidden in all types of critical biotopes. The key biotopes and elements preserved in NW Russia are similar to woodland critical habitats in NSF and the Baltic (Latvia, Estonia, Lithuania) countries (Timonen et al., 2010). The main types of key biotopes include (1) forest patches around peatlands, small lakes, and springs; uneven-aged forest patches; (2) gaps after windthrows; (3) regionally rare tree species; (4) old trees; (5) trees with bird nests and hollows; (6) snags; and (7) high stumps and large downed deadwood of different decay classes. Since 2001, biodiversity conservation has been actively incorporated into forest management per forest certification criteria (Chap. 21). In addition to the mandatory forest management restrictions within key biotopes, some nonmandatory protected key biotopes and key elements (retention forest patches and individual structures) with possible buffer zones around these protected areas are also left unharvested (Shorohova et al., 2019 and citations therein). Evidence related to the quantity of key biotopes and elements is scarce. One case study of ten FSC-certified forest companies demonstrated that the area of key biotopes inside clear-cut areas (data from 2005 to 2014) varied from 1 to 13% with a mean of 6%; therefore, most key biotopes are protected outside the areas planned for harvesting (Ilina & Rodionov, 2017).

The practice of leaving retention tree patches and critical elements in harvesting areas began with model forests in 2000 (Elbakidze et al., 2010; Romanyuk et al., 2001) and later became common in NW Russia. Since the 1990s, selective logging has become more common. After 2000, the share of selective harvest in NW Russia varied among regions, ranging from 2 to 58% with a mean of 22% (Federal Forestry Agency, 2013).

The growing decline in forest resources in European Russia and southern Siberia has brought into question the sustainability of harvests at the regional scale (Shvidenko & Nilsson, 1996). The annual allowable cut (AAC) assessment is based on the sustained yield model derived from the German classical school (Antanaitis et al., 1985; Sukhikh, 2006). The inconsistency of this approach has been demonstrated (Sheingauz, 2007), with one of the main critiques being the lack of integration of several important issues, such as the impact of natural disturbances, the uneven-aged nature of forest stands (Shvidenko & Nilsson, 1996), and regional variation in timber demand. There exists a means of accounting for these issues within AAC calculations (Sheingauz, 2007); however, this calculation has not been implemented in practice.

Multiple studies have shown that the officially established AAC (about 650–700 million $m^3 \cdot year^{-1}$ for all of Russia during the last decade) is about twice as high as the potential sustainable harvesting level should be, according to the SFM principles (Sokolov, 1997; Sukhikh, 2006). Therefore, the official information on the significant underutilization of AAC in Russia in recent decades must be cited with caution. Significant hidden overharvesting was typical for individual forest enterprises in northern European Russia, south-central Siberia, and the Russian Far East between 1950 and 1990 (Koldanov, 1992; Sheingauz, 2007).

Increasing wood production and a shift to intensive forest management (Karjalainen et al., 2009; Karvinen et al., 2011) have been much discussed over the last 30 years. Alternatively, adaptive management for maximizing resilience and the sustainability of forests under climate change has been recommended (Chap. 13; Chapin et al., 2007; Karpachevsky, 2007; Naumov et al., 2017; Nordberg et al., 2013). The concept promotes selective felling practices and preserving key biotopes and elements in parallel with research and monitoring of the results of their practical implementation. Its implementation, however, is affected by discrepancies between existing forestry regulations and sustainability (Karpachevsky, 2007; Kulikova et al., 2017; Sinkevich et al., 2018; Yanitskaya & Shmatkov, 2009). The diverse natural and socioeconomic conditions across the country and the variable legacies from past forestry activities should be considered in forest management planning (Lukina et al., 2015; Naumov et al., 2017; Shvarts, 2003; Shvidenko & Schepaschenko, 2011; Sinkevich et al., 2018).

1.5 Role and Need for a Restoration Framework

If the forest is heavily used and degraded, sustainable ecosystem management for multiple ecosystem values and services is not directly possible (see the definition of FEM, Box 1.1). This is the case in some southern boreal regions, especially in Fennoscandia, where forest use has been most intensive and long lasting (Berglund & Kuuluvainen, 2021; Kuuluvainen, 2009). In these cases, a lengthy restoration period may be required before FEM is possible (Fig. 1.2; Halme et al., 2013; Seymour, 2005). This long period occurs because forest landscapes show considerable inertia to changes in management, and there can be significant time delays in attaining favorable management status goals, depending on the level of restoration activities and the past use of the forest.

Finland and Sweden provide examples of a situation where restoration is needed before FEM becomes possible (Fig. 1.2; Chap. 18). Boreal forest management has been intensive in these regions and based on even-aged forest management and clear-cut harvesting. This practice, combined with short cutting rotations relative to natural disturbance cycles, has produced landscapes of young, structurally simplified forests that fall outside the NRV of the regional natural heterogeneous landscapes, which are characterized by old uneven-aged forests, big trees, abundant deadwood, and a relatively high structural variability (Kuuluvainen, 2009). Here, restoration using natural disturbance–based management is needed before FEM can be applied (Berglund & Kuuluvainen, 2021).

At present, restoration has been carried out in protected areas for habitat management purposes (Similä & Junninen, 2012). The first controlled burning for restoration purposes in Finland, and possibly anywhere in Europe, was conducted on a small, wooded island surrounded by peatland in Patvinsuo National Park in 1989. Twenty years later, the burned site is a hotspot for polypore fungi, hosting many red-listed species (Similä & Junninen, 2012). Experiences from such experiments can also be used for restoring managed forests (Vanha-Majamaa et al., 2007).

Although heavily exploited for a long time in its southern parts, the boreal zone still encompasses half of the world's unexploited forests (Burton et al., 2010). These large areas of relatively unmanaged boreal forest are found in Canada and Russia. Over the last 50 years, however, harvest operations have increased significantly in Canada, reaching the highest ratio of cutting globally by the end of the 1990s (Perrow & Davy, 2002). Consequently, Canadian restoration goals focus on protecting natural forests (passive restoration), restoring degraded areas related to mining, and applying sustainable forest management practices. Recently, some experiments to restore the natural forest structure have used commercial thinning operations to convert plantations from even-aged to irregular or uneven-aged stands (Schneider et al., 2021). Similarly, Thibeault et al. (submitted) also demonstrate that planting conifers to replace fallow lands not only maintains carbon sequestration capacity but also contributes to counteracting the decrease in native conifers observed since colonization in northern Québec (Marchais et al., 2020).

In Russia, there have been only a few studies on ecological restoration, with research focused on broadleaf forests (Korotkov, 2017), peatlands (Minayeva et al., 2017), and individual species (Baerselman, 2002). Green desertification, a form of degradation, has been observed in the northern bioclimatic zones of boreal Asian Russia (Yefremov & Shvidenko, 2004). Ongoing climate change has increased the area burned as well as fire frequency and severity (Shvidenko & Schepaschenko, 2013), which has led to the marked transformation of forest ecotopes. In harsh environmental conditions, e.g., on permafrost, in mountains, and within zonal ecotones, such burned areas cannot restore their productive potential and forest cover for decades or even centuries without human assistance. Similar regeneration failures have also been reported in Canada (Whitman et al., 2019) and are expected to increase in the future (Splawinski et al., 2019).

We are therefore in urgent need of effective methods for restoring forests impacted by intensive management or other human disturbances. Nonetheless, ecological restoration is far from a straightforward template-based model, especially considering the uncertainties caused by ongoing global change. These changes are likely to affect (directly and indirectly) terrestrial ecosystems, but restoration planners rarely account for such future impacts. Restoration ecology requires novel approaches and more interdisciplinary scientific collaboration to address these new challenges. Global change occurs at multiple scales, as do degradation and restoration; thus, it is necessary to consider species, processes, and interactions from the microhabitat to landscape scale to ensure efficacy and success in future management approaches. In the light of global change, the priority lies not only on conserving but also on restoring forest ecosystems, taking their resilience to global change into account (Chap. 17). Even if restoration represents a major challenge in boreal forests, the research effort in this field is limited relative to that in other biomes, e.g., tropical forests. We therefore need to apply ecosystem-based management strategies and implement effective practices to restore degraded forest systems if we want to safeguard forest biodiversity and ecosystem services (Chap. 25; Aronson & Alexander, 2013; Hof & Hjältén, 2018; Moen et al., 2014).

1.6 A New Context Challenging the FEM Paradigm

1.6.1 Climate Change in the Boreal Forest

Boreal forests are experiencing rapid climate change and increased pressure from resource extraction and land use. As the boreal biome is located at higher latitudes, it is particularly affected by the changing climate (Bush & Lemmen, 2019; IPCC, 2014; Price et al., 2013); for example, modified climate patterns are already affecting regional disturbance regimes (Hanes et al., 2019; Safranyik et al., 2010; Seidl et al., 2017). By the end of the twenty-first century, under the business-as-usual IPCC climate scenario (RCP8.5), the average temperature of the boreal biome is predicted to rise from −4.3 to 4.2 °C, with some regions attaining average increases of 10 °C (based on the data of Thrasher et al. (2012) with the CanESM2). In Russia, for example, under the RCP8.5 scenario, the average annual temperature is expected to increase from 6 to 9 °C by 2100 over much of the country (even higher in some regions), and uncertain, yet likely small, increases of the precipitation are predicted in continental Russia. Similarly, only a slight increase in total precipitation is projected during this period in other extensive areas of the boreal zones.

These changes are likely to be accompanied by changing disturbance regimes having a diversity of potential outcomes. In most regions where fire is an important disturbance agent, the number of fires and the annual area burned are expected to increase (Boulanger et al., 2014; IPCC, 2014). In Russia, for instance, recent evidence points to a new fire regime of greater area burned and an increased fire frequency and severity (Bartalev & Stytsenko, 2021; Bartalev et al., 2015, 2020), which has led to the destruction of forest resources of dozens of forest enterprises. Disturbances such as fire are already limiting commercial forestry in many boreal forest areas (Gauthier et al., 2015b), and forestry activities are expected to be even more limited as climate change–related disturbances increase (Boucher et al., 2018; Hof et al., 2021). Moreover, direct impacts of heat waves (e.g., central Russia in 2010, western Siberia in 2012, northern central Siberia in 2013) may substantially decrease forest productivity in Russian boreal forests because of higher temperatures and greater water stress (Bastos et al., 2014). Drought frequency is expected to rise, and the overall regional climate is projected to become dryer, resulting in potential effects on forest productivity (Girardin et al., 2016; Shvidenko et al., 2017; Tchebakova et al., 2009).

Although future climate change may be more conducive to insect outbreaks (e.g., Navarro et al., 2018b; Régnière et al., 2012; Safranyik et al., 2010)—allowing the insects to migrate north or east of their current range—it may also favor a lack of synchroneity with their hosts' phenologies (Pureswaran et al., 2015), thereby reducing their potential effect. However, recent work suggests that insects can evolve rapidly to synchronize with hosts (Bellemin-Noël et al., 2021; Pureswaran et al., 2019). Thus, invasive insects could produce outbreaks in regions where a cold climate previously prevented their colonization (Kharuk et al., 2019; Safranyik et al., 2010).

Moreover, although current human population densities in most boreal regions remain relatively low, land use and excessive natural resource exploitation add further stresses to the boreal biome (Gauthier et al., 2015a). Development-related air pollution represents another potential stressor (Bytnerowicz et al., 2007). Landscape fragmentation is increased through the cumulative effects of land-use activities, including forest harvesting, urbanization, transportation infrastructure, energy and mineral development (e.g., Chap. 19; Schneider et al., 2003). Market forces and global events also reduce or heighten the pressure on forest resources—the 2008 economic recession provided an example when global economic forces lowered harvesting levels in Canada. Such socioeconomic hazards and random elements may compound the climate change–related impacts by reducing the forest's adaptive capacity (Millar et al., 2007). These events also render the entire socioecological forest system even more unpredictable (Nocentini et al., 2017). All these effects have consequences on our ability to manage forests sustainably in the future.

1.6.2 Challenging the FEM Paradigm

As the extent of potential impacts of climate change on forests became increasingly evident by the early 2000s, the scientific community began to present some criticisms of FEM and propose alternative management approaches (Messier et al., 2019; Millar et al., 2007). A prominent critique of FEM relates to the relevance of using the past NRV as a management reference. The main questions centered on whether establishing baseline conditions from past conditions could create ecosystems ill adapted to rapidly evolving, non-analog future conditions (Millar et al., 2007).

Millar et al. (2007) identified three types of adaptive strategies to help forest ecosystems face future climate conditions: resistance, resilience, and transition. First, heightening forest resistance requires management strategies and practices that focus on maintaining or restoring forest conditions that are of high value to society. Such an example would be maintaining specific forest conditions to help preserve an endangered species or a high-value plantation. Second, bolstering forest resilience demands actions that ensure forests preserve their ability to return to the desired state. The return to the closed forest state after disturbance in areas where successive disturbances can cause regeneration failure is one crucial resilience aspect to focus on (Blatzer et al. 2021; Kuuluvainen & Gauthier, 2018; Splawinski et al., 2019). The third strategy involves helping ecosystems adapt to projected future conditions. One common example of such a strategy is related to assisted migration, where seedlings from populations adapted to future climatic conditions for the region are used in plantations or as seed sources (Chap. 30; Pedlar et al., 2012; Ste-Marie et al., 2011). Several frameworks, tools, and field guides have since been developed to help forest managers analyze the vulnerability of particular forest ecosystems to future change, and to prepare management plans and silviculture practices to address upcoming changes (Chap. 12; Edwards et al., 2015; Gauthier et al., 2014; Handler et al., 2020; Nagel et al., 2017; Swanston et al., 2016).

Aquatic environments are another neglected aspect of FEM. These water bodies contribute to the high complexity of boreal forests and are essential to forest functioning (Chap. 29). Aquatic environments provide essential resources for terrestrial species, such as irreplaceable habitats for the larval stages of multiple species and the export of essential fatty acids and nutrients toward terrestrial fauna and flora (Fritz et al., 2019; Martin-Creuzburg et al., 2017). Water-covered lands represent about 30% of the world's boreal forest area, ranking the boreal biome as one of the world's major sources of freshwater (Benoy et al., 2007). Terrestrial and aquatic environments are in constant interaction in the boreal landscape. Whereas most organic matter and energy fluxes are sourced from the forest and then transported to aquatic habitats by precipitation, freshet, and wind (Solomon et al., 2015; Tanentzap et al., 2017), freshwater to land fluxes are greater in terms of energy and nutritional quality (Gladyshev et al., 2019). Terrestrial organic matter traveling from land to aquatic environments is processed by aquatic food webs (Grosbois et al., 2020; McMeans et al., 2015) and returned to terrestrial environments via respiration (Lapierre et al., 2013) or animal movements, e.g., the emergence of aquatic insects, as *boomerang fluxes* (Scharnweber et al., 2014). Aquatic environments are therefore an integral part of boreal forest functioning at the landscape scale and contribute to the complexity of the boreal forest; thus, they are components that must be considered within any future FEM framework.

The recognition of forest ecosystems as complex adaptive systems has also become part of the conceptual sphere of forest management. This shift in thinking arose from the understanding that many feedback loops characterize forest ecosystems, each strongly influenced by their initial conditions, for which the outcomes have a relatively low level of predictability (Nocentini et al., 2017). This approach acknowledges the diversity of stand responses; therefore, silviculture implemented under this concept should not aim to homogenize forest stands but rather adapt to the stands themselves (Nocentini et al., 2017).

These approaches question the command-and-control idea used in traditional forestry, a practice that has simplified forest structure to render the system more fragile and vulnerable in the face of stressors such as pollution, climate change, and fragmentation (Messier et al., 2019; Millar et al., 2007; Nocentini et al., 2017). Moreover, the complex adaptive system framework stresses that the future is highly uncertain, and the entire system outcomes have low predictability (Chap. 28; Messier et al., 2019; Millar et al., 2007; Nocentini et al., 2017). Thus, a portfolio approach is required (Gauthier et al., 2014; Millar et al., 2007), i.e., the use of a diversity of solutions to address one particular challenge. An example of this approach would be using a mixture of provenances when replanting a post-disturbance area to ensure some trees will be successful under future conditions. This approach contrasts markedly with more deterministic and optimization strategies, which work best under a set of known conditions. Permanent outcome monitoring is considered a vital tool for selecting, controlling, and correcting forest management decisions. At first glance, these novel approaches proposed to adapt forests to future climate change may seem quite different in their respective philosophies from the original FEM concepts. Nonetheless, many of the principles of the FEM approaches remain essential and can be complemented by these novel approaches (Messier et al., 2019). Management based on the past natural range of variability will remain adequate in certain regions or for selected periods. For instance, in the boreal forest in northwestern Québec, projected burn rates remain within the natural range of variability of the past 8,000 years (Fig. 1.3). They thus can serve as a basis for management into the century. However, new situations could emerge that profoundly change natural ecosystems, notably in regions dominated by fire-adapted species (Baltzer et al., 2021).

This book examines the concepts of FEM in the context of global change. The chapters in this book also identify potential conceptual improvements and adjustments required to address the challenge of future global change and associated uncertainties. Therefore, this book aims to revise the principles of FEM to ensure managed forests remain resilient in the face of future changes. To achieve this goal, we build a new framework in collaboration with forest researchers studying all regions of the boreal biome and highlight new issues, challenges, and trends in forest management in a changing world. We also provide novel paradigms for the future of boreal forest management, including the need to consider social concerns (Chaps. 21 and 22), the interactions between forest and aquatic ecosystems (Chap. 29), the role of ecological restoration (Chaps. 17 and 18), the potential of new tools facing climate change (Chaps. 26 and 27), the complexity of forest ecosystems (Chap. 28), and the challenges and trends facing the future (Chap. 31).

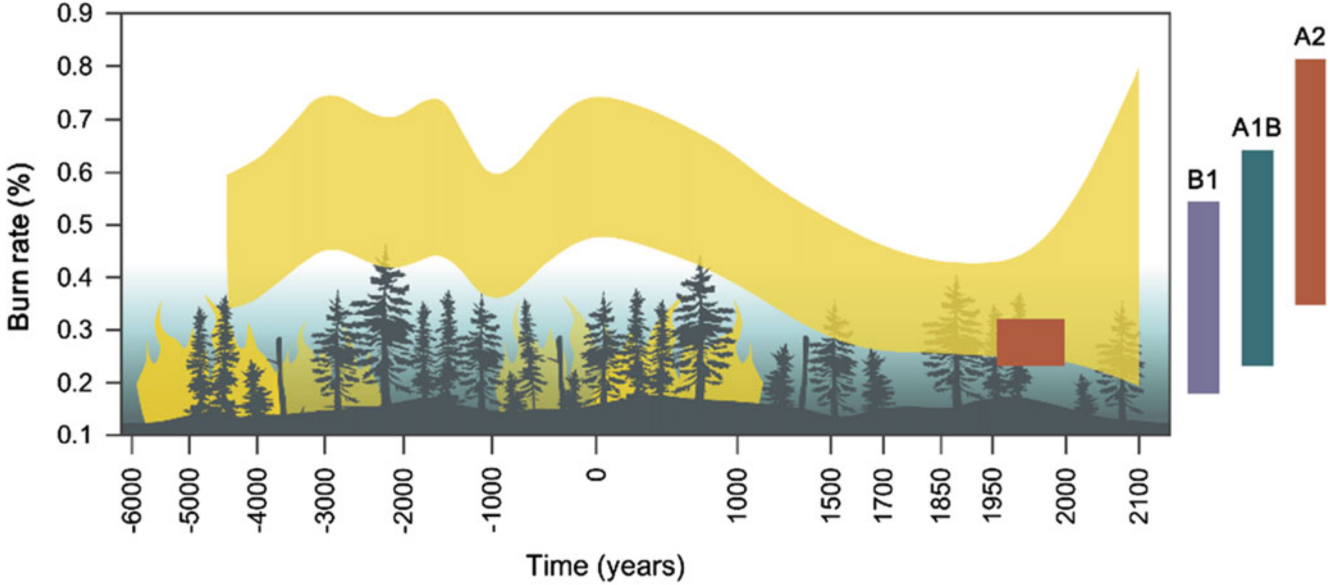

Fig. 1.3 Long-term variability of the burn rate for the boreal forest of northwestern Québec. The *red box* on the figure represents the current burn rate. The projected future burn rates (*B1*, *A1B*, *A2*) are within the natural range of variability although at the upper margin, suggesting that FEM principles can apply in the region for the next century. Projections for 2100 of annual area burned were made using simulated monthly drought-code data collected from an ensemble of 19 global climate models and forcing experiments run against three IPCC scenarios (*B1*, *A1B*, *A2*). Modified with permission of CSIRO Publishing from Bergeron et al. (2010); permission conveyed through Copyright Clearance Center, Inc.

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