Chapter 15
Silviculture of Mixed-Species and Structurally Complex Boreal Stands

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Abstract Understanding structurally complex boreal stands is crucial for designing ecosystem management strategies that promote forest resilience under global change. However, current management practices lead to the homogenization and simplification of forest structures in the boreal biome. In this chapter, we illustrate two options for managing productive and resilient forests: (1) the managing of two-aged mixed-species forests; and (2) the managing of multi-aged, structurally complex stands. Results demonstrate that multi-aged and mixed stand management are powerful silvicultural tools to promote the resilience of boreal forests under global change.

15.1 Introduction

Silvicultural practices have long been used to encourage the provision of desired ecosystem goods and services to landowners and society (Puettmann et al., 2009). The selection and implementation of specific practices are driven mainly by ownership objectives and logistical opportunities and constraints. Consequently, as management objectives have changed over the last few decades from a focus on timber production

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to managing for a broader set of goals, e.g., biodiversity, recreation, and resilience, a more diverse suite of silvicultural practices had to be applied (Puettmann et al., 2009). On public lands, societal shifts have led to increased recognition of the importance of ecosystem services such as wildlife habitat, recreational opportunities, spiritual values, or biodiversity, in addition to or instead of timber production. Furthermore, recent concerns regarding biodiversity loss, reduced productivity (Chap 1; Table 1.1), and forest resilience in the face of global change (Chap. 1; Table 1.2) require applying a broader set of silvicultural practices than in the past to manage forests for a novel, uncertain future (Puettmann, 2011; Shvidenko & Apps, 2006).

The selection of silvicultural systems has traditionally been justified by understanding the dominant natural disturbance regimes (Bradshaw et al., 1994). In unmanaged boreal forests, natural regeneration is often initiated following disturbance by fire, insects, or windstorms (Kuuluvainen & Grenfell, 2012). The theory of natural disturbance emulation, holds that clear-cutting simulates large high-severity perturbations, e.g., fire, but this silvicultural approach leads to less standing and downed woody debris and different soil conditions than encountered following a fire (Bergeron et al., 2002; Kuuluvainen & Grenfell, 2012; Moussaoui et al., 2016a, 2020). Over the last few decades, ecosystem-based forest management has become a dominant management paradigm in many countries (Chap 1). Correspondingly, our understanding of natural disturbance regimes and their impacts on succession has expanded to underline the role and influence of spatial and temporal variability and environmental legacies (Bergeron & Harvey, 1997; Montoro Girona et al., 2018a). Thus, rather than having a narrow focus on variables such as the average fire return interval or fire size, silvicultural practices should reflect the full suite of disturbance frequencies and severities, especially small-scale disturbances (Kuuluvainen & Grenfell, 2012). Together with the shift in the abovementioned landowners' objectives, the recognition of the role of disturbances of wide-ranging severity and size has encouraged landowners to consider a more diverse range of silvicultural practices. As an example of the practical implications of this shift in thinking, variable retention has gained global attention (Gustafsson et al., 2012; Kuuluvainen & Grenfell, 2012; Moussaoui et al., 2016b).

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Both the increased diversity of management objectives and an improved understanding of the variability created by natural disturbances present challenges, with their relative importance changing depending on ownership and the particular ecological and social context. Furthermore, addressing these factors will become even more complicated in response to social and ecological trends associated with global change (Puettmann, 2011). For example, although using the variability of natural disturbance patterns to manage for multiple ownership goals had received much attention in the past (Franklin et al., 2018; Kuuluvainen & Grenfell, 2012), practical suggestions to encourage the adaptive capacity, e.g., resilience, of forests to combat the negative impacts of global change are scarce (Puettmann & Messier, 2019). This adaptive capacity is of particular importance, as future conditions are expected to be increasingly influenced by human-caused rather than natural drivers; thus, managing for resilience and adaptive capacity will likely increase in importance (Puettmann, 2011).

An increased focus on a broader set of ecosystem services and the variability of natural disturbance regimes has led to an interest in managing forests within a wider envelope of structural and compositional conditions. This vision aligns with management approaches for resilience, as ecosystem adaptation mechanisms are based on maintaining or even enhancing functional diversity—species with different traits that, for example, respond differently to various disturbance agents—and cross-scale interactions, e.g., disturbances producing high structural and compositional variability within stands (Puettmann & Messier, 2019). In this context, this chapter highlights silvicultural practices aimed at encouraging heterogeneous species composition and stand structures in boreal forests, as quantified by tree species composition and vertical structure, respectively, to promote resilience to global change.

Compared with monocultures, mixed-species forests provide a more comprehensive suite of ecosystem services (Hector & Bagchi, 2007; Himes & Puettmann, 2020) and encourage a broader range of stand structures (Pretzsch et al., 2017). Stand structural variability is managed using a variety of approaches, from the classic uneven-aged management (*Plenterwald*) (O'Hara 2014) to variable-retention harvests (Gustafsson et al., 2012). In contrast to the classical *Plenterwald*, variable-retention harvests emphasize spatial variability and thus ensure that a variety of successional stages are present in stands, including early seral and older stages (Franklin et al., 2018). At the same time, the importance of ensuring a variety of ecosystem services, especially those related to biodiversity, leads to increased attention to other structural elements, such as understory vegetation, snags, and downed wood. Greater knowledge of species mixtures and heterogeneous stand structure supports practices that improve the resilience of forest stands, especially in a context of global change (Puettmann & Messier, 2019).

15.2 Silvicultural Systems and Complexity

The choice of a silvicultural system influences structural and compositional conditions and their evolution (Kuuluvainen et al., 2012; Puettmann et al., 2009; Raymond et al., 2009). Silvicultural systems influence structural diversity, which can range from simple single-canopy layer stands in even-aged systems to multiple canopy layers in uneven-aged stands. The spatiotemporal arrangement of management practices, e.g., gap creation or patch thinning, and the retention of structural attributes, e.g., choice of species and trees for retention at stand and landscape scales, can also maintain or increase complexity (e.g., Bauhus et al., 2009; Gustafsson et al., 2012). Furthermore, within-stand heterogeneity of topography, soil conditions, and available resources promote structural and species diversity, especially in late-successional forests (Moussaoui et al., 2019). In contrast to traditional efforts to homogenize forests for production efficiency (Puettmann et al., 2009), silvicultural systems that create diverse ecological niches (e.g., irregular shelterwood and hybrid selection-cutting systems) or that incorporate within-stand variability, such as canopy gaps or vertical structure in mixed-species stands are expected to facilitate species coexistence and diversity (Burton et al., 1999; Raymond & Bédard, 2017). Moreover, silvicultural systems that maintain continuous forest cover are more likely to sustain structural attributes, associated microhabitats, and, thus, biodiversity over time (Kim et al., 2021; Martin et al., 2020; Moussaoui et al., 2016b; Peura et al., 2018). The selection of a given silviculture option varies as a function of current stand and landscape conditions, ownership goals, and logistical opportunities and constraints. In the following sections, we illustrate two management examples to highlight options for managing productive, resilient boreal forests: (1) managing for two-aged mixed-species forests; and (2) managing for multi-aged, structurally complex forests.

15.3 Silviculture of Two-Aged Mixed Forests

Two-aged mixed stands, which combine fast-growing, early-successional, and light-demanding tree species (nurse trees) with late-successional and shade-tolerant tree species (target trees), is a management concept that has gained interest over the past two decades (Fig. 15.1; Paquette & Messier, 2010; Rytter et al., 2016). The faster-growing nurse trees provide shade to limit competing vegetation (Lieffers & Stadt, 1994) and protect smaller seedlings and saplings against late spring frost (Filipescu & Comeau, 2011). Nurse trees also facilitate the establishment of more slow-growing target trees and improve their stem form (Middleton & Munro, 2002; Paquette et al., 2006; Pommerening & Murphy, 2004). The risk of insect attack and the related impacts are reduced in mixed stands because the presence of multiple tree species reduces the impact of host-specific insects (Campbell et al., 2008; Lavoie et al., 2021; Taylor et al., 1996; Zhang et al., 2018). The risk of root disease is also reduced in mixed stands (Gerlach et al., 1997). Slow-growing crop tree species can

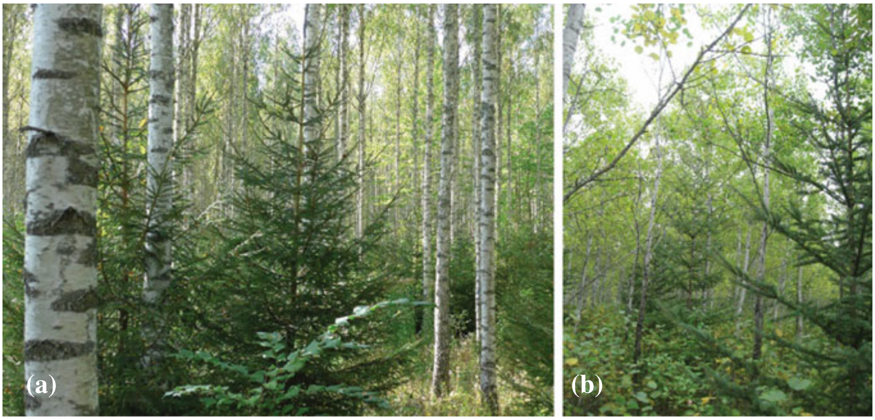

Fig. 15.1 Managing two-aged stands is more complex than managing monocultures; however, two-aged stands offer more adaptability to uncertain future conditions. **a** Silver birch (*Betula pendula* Roth)–Norway spruce in Sweden and **b** aspen–white spruce in Alberta, Canada are examples of boreal mixedwoods that can be managed as two-aged stands. *Photo credits* **a** Lars Rytter, **b** Phil Comeau

also be difficult to establish without protection from a nurse crop. In these conditions, facilitative interactions can be more prominent than competitive interactions, at least during the early stages of stand development (Pretzsch et al., 2017).

Under selected conditions, mixed-species forests are often more productive than single-species forests (Pretzsch et al., 2017). This is particularly the case for two-aged stands where transgressive overyielding often occurs, i.e., the mixture is more productive than the monoculture of the most productive species in the mixture (Kweon & Comeau, 2019; Pretzsch et al., 2017). Two-aged management can also accelerate natural succession from shade-intolerant to mixedwood composition in second-growth forests (Prévost & DeBlois, 2014; Smith et al., 2016). Thus, with two-aged stands, greater biodiversity, resilience, and a more diversified portfolio of ecosystem services can be combined with increased stand growth and carbon sequestration (Felton et al., 2016; Pretzsch et al., 2017).

Several tree species combinations are relevant for this type of management, making it applicable to a range of site conditions. Such examples in Scandinavia are planted or naturally regenerated stands combining birch (*Betula* spp.) as nurse crops with Norway spruce (*Picea abies* L. Karst.) as the target tree species underneath (Mård, 1996). In Canada, similar stands with trembling aspen (*Populus tremuloides* Michx) and either planted white spruce (*Picea glauca* (Moench.) Voss.) (Kabzems et al., 2016; Lieffers et al., 2019; Pitt et al., 2015) or other natural mixtures of spruce and fir (Prévost & DeBlois, 2014; Smith et al., 2016) can be managed as two-aged stands. Such multispecies stands may be more productive than single-species stands, with a transgressive overyielding up to 20% (Kweon & Comeau, 2019). The use of a fast-growing nurse crop may be a cost-effective strategy for raising new forests because the nurse crop can be harvested during the early phase of stand development and provide earlier income for the manager (Löf et al., 2014). Nurse crops may benefit the establishment of the more shade-tolerant understory species on some sites experiencing global change.

Conceptually, the presence of more than one tree species may give managers greater flexibility in their future management through increased possibilities to adapt to changing societal objectives, especially if species and/or provenances are chosen to counter the potential impacts of global change (Puettmann, 2011; Puettmann & Messier, 2019). However, the management of such stands is more complicated than that for monocultures. The challenge occurs when facilitative interactions are overridden by competitive interactions, i.e., when the competition from the nurse crop decreases the growth of the understory tree species (Pretzsch et al., 2017). If thinning and harvesting of the nurse crop is not timed to the needs of the understory tree species, the latter may stagnate in growth, and mortality may increase. In most cases, the density management of the two (or more) tree species requires interventions at different times, resulting in multiple entries, each with smaller harvest yields, compared with even-aged monocultures. Despite the additional management costs, two-aged management can yield better economic results than monoculture stands (Valkonen & Valsta, 2001) and offset these higher management costs (Kabzems et al., 2016). For example, gains in volume in aspen–white spruce mixtures can yield up to 17% additional volume over that provided by a pure spruce stand (aspen plus spruce) when harvested at 90 years of age, and 41% more volume if aspen and spruce are harvested at 60 and 90 years of age, respectively (Kabzems et al., 2016).

Tending practices, including precommercial thinning, the removal of early-successional species within a prescribed radius of selected trees using herbicides, cutting or snapping treatments, and the application of herbicides in patches or strips, can be used to reduce the density of the early-successional species in the overstory and increase the growth of the subordinate species (Pitt et al., 2015; Prévost & Charette, 2017). Mixtures of faster-growing early-successional species with longer-lived late-successional species can also improve the self-pruning of the lower branches of dominant trees and the quality and value of stems because of the complementary use of vertical space and shading of lower boles by the conifers (Prévost & Charette, 2017; Puhlick et al., 2019). Precommercial thinning of shade-intolerant deciduous species, such as aspen and birch, taking care to protect advance conifer regeneration, can facilitate recruitment to upper classes and, in this way, accelerate natural succession and/or conversion of stands toward a more complex composition and structure (Prévost & Charette, 2017). Similarly, when trees reach commercial dimensions at later stages, partial cutting can promote advanced conifer regeneration growth—and limit suckering in aspen stands—before final overstory removal (Montoro Girona et al., 2018b; Prévost & DeBlois, 2014; Smith et al., 2016).

Managing two-aged stands is an appealing concept that merits further development, especially in boreal forests with their low taxonomic diversity but which contain species of contrasting growth habits. Additional gains in productivity and wood quality could, for example, be expected by combining this approach with genetically improved material, exotic tree species, e.g., *Poplar* spp. hybrids, and nitrogen-fixing tree species. In addition, the nurse-crop system requires further development to identify appropriate regimes for the thinning of the nurse crops to support the successful development of various target tree species. Improved knowledge of yield and those factors influencing yield outcomes is needed to make and support economically sound decisions. Despite the benefits, care must be exercised to avoid increasing the risk of large catastrophic fires that may result from increased conifer abundance and reduced broadleaf abundance and from greater aridity due to global change. Two-aged stands also provide more structural diversity, habitats, and ecosystem services than single-aged monocultures (Berger & Puettmann, 2000).

15.4 Silviculture of Structurally Complex Stands

Although stand-replacing fires are the main natural disturbance in boreal forests, detailed investigations into the variability within and among fires have shown that parts of these forests escape catastrophic fires and thus develop complex multicohort, uneven-aged structures (Fig. 15.2; Boucher et al., 2003; Kuuluvainen & Grenfell, 2012). In the absence of stand-replacing disturbances, low- and moderate-severity disturbances, caused by agents like wind, insects, and pathogens, initiate regeneration processes (Kuuluvainen & Grenfell, 2012; Martin et al., 2019, 2020; Pham et al., 2004). These findings suggest that silvicultural systems other than clear-cutting could be applied to maintain or enhance forest structural complexity (Bergeron & Harvey, 1997; Groot, 2002; Lieffers et al., 1996). Examples include traditional uneven-aged systems (e.g., selection cutting, *Plenterwald*) that mimic small-scale natural variability in boreal forests composed of long-lived conifers, such as black spruce (*Picea mariana*; Groot, 2002; Ruel et al., 2013), Norway spruce, and Scots pine (*Pinus sylvestris*) stands (Lähde et al., 2010; Pukkala et al., 2010). In eastern Canada, operational selection-cutting systems maintain complex stand structures, abundant coarse woody debris, and greater species diversity after the initial harvest in naturally uneven-aged black spruce forests (Ruel et al., 2013). There is a lack of data on the long-term productivity of uneven-aged managed boreal forests and, more broadly, for forests regenerated after partial cutting. Specific concerns relate to post-harvest windthrow because of poor rooting conditions and the slow growth rates observed under northern latitudes (Bose et al., 2014; Kuuluvainen et al., 2012; Montoro Girona et al., 2019). However, the advantages of uneven-aged managed forests in terms of maintaining wildlife habitat, species diversity, carbon storage, and other ecosystem services can counterbalance the negative impacts of partial cutting and justify management choices, especially when a variety of management goals are implicated (Ameray et al., 2021; Kuuluvainen et al., 2012; Montoro Girona et al., 2016; Peura et al., 2018; Ruel et al., 2013).

Irregular shelterwood systems, originally called *Femelschlag*, can be more suitable to irregular uneven-aged stands—stands with heterogeneous spatial patterns, stand structures, and species composition—than selection systems, especially when these stands comprise species having a wide range of functional traits, e.g., life span

Fig. 15.2 In the absence of catastrophic stand-destroying disturbances, secondary disturbances enable the development of complex stand structures; **a** an old-growth unmanaged black spruce stand and **b** a balsam fir–yellow birch irregular stand managed by irregular shelterwood in Québec, Canada. *Photo credits* **a** Maxence Martin, **b** Patricia Raymond

and shade tolerance (Klopcic & Boncina, 2012; Lieffers et al., 1996; Raymond et al., 2009). The different variants and the potential range in resulting spatial and structural outcomes make irregular shelterwood systems highly adaptable and able to simultaneously address various management goals (Boncina, 2011; Raymond et al., 2009; Suffice et al., 2015). In eastern Canada, for example, continuous-cover irregular shelterwood can regenerate sub-boreal balsam fir (*Abies balsamea*)–yellow birch (*Betula alleghaniensis*) stands driven by cyclic moderate-severity disturbances, e.g., spruce budworm (*Choristoneura fumiferana*), while maintaining irregular stand structures and microhabitat diversity (Martin & Raymond, 2019; Raymond & Bédard, 2017). Expanding-gap irregular shelterwood systems have also proven useful for managing forests dominated by balsam fir and red spruce (*Picea rubens*) in North America (Saunders & Arseneault, 2013) and stands of silver fir (*Abies alba*) and Norway spruce in Europe (Heinrichs & Schmidt, 2009; Klopcic & Boncina, 2012). Several experiments and studies have documented the use of selection systems and irregular shelterwood systems to transform even-aged stands into uneven-aged stands. However, this process takes time and can be challenging, particularly for the establishment and development of regenerating cohorts (Heinrichs & Schmidt, 2009; Ligot et al., 2020).

Finally, partial-harvest operations, as an overarching concept that includes selection, shelterwood systems, and others, emphasize the importance of structural legacies (Franklin et al., 2018; McIntire et al., 2005) and provide a means of promoting structural and species diversity as an alternative to clear-cutting (Burton et al., 1999; Lieffers et al., 1996). Variable-retention cutting, a variant of clear-cut systems with the retention of overwood, can also increase structural and compositional diversity (Moussaoui et al., 2016a, 2016b). In a meta-analysis of retention harvests, species richness in retention patches was similar to that of primary boreal forests (Mori & Kitagawa, 2014), with mobile animals, such as birds and arthropods, doing well after retention cutting, whereas vascular plant diversity remained stable, and epiphyte diversity declined. This global analysis also indicated that responses did not differ between dispersed and aggregated retention. However, the highest variability of responses was found when both patterns were combined (Mori & Kitagawa, 2014), underscoring the benefit of flexibility in the layout of partial-harvest operations. Moreover, any silvicultural prescriptions designed in the context of sustainable forest management should include the retention of vital structural attributes, such as standing dead and large live trees, to prevent biodiversity loss (Burton et al., 1999; Puettmann & Messier, 2019).

15.5 Conclusions

The silviculture of boreal forests is dynamic because management objectives must constantly adjust to changing societal needs and ongoing global change but also maintain or enhance the adaptive capacity of forest ecosystems. The homogenization and the simplification of forest structures, caused by past harvesting and management practices, has induced a low resilience of boreal forests to global change (Felton et al., 2016). Consequently, productive boreal forests are being simplified, as areas are increasingly covered by even-aged stands of a limited number of conifer species and organized with little compositional and structural diversity (Felton et al., 2016). If simplification of the boreal forest ecosystems and biodiversity loss continues, forests will become less adaptable and resilient to global change (Puettmann & Messier, 2019). Relying on the principles of increasing within-stand compositional and structural variability, we encourage the use of multi-aged and mixed-species management approaches to increase resilience. However, it is essential to work at other scales by encouraging the diversification of forest structures, i.e., age classes and species, and by limiting fragmentation and biodiversity losses at the landscape scale. Silvicultural planning for sustainable management also requires accounting for global change, altered natural disturbance regimes and rapidly evolving socioeconomic needs. Consequently, it is necessary to work in the context of complex adaptive systems (nonlinearity, heterogeneity, and multiple scales), re-evaluate constantly forest management and silvicultural practices, and adopt resilience as main goal to ensure the long-term sustainability of boreal forests (Kuuluvainen et al., 2015; Montoro Girona et al., 2018b; Puettmann et al., 2009).

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