Chapter 16
Innovative Silviculture to Achieve Sustainable Forest Management in Boreal Forests: Lessons from Two Large-Scale Experiments

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Abstract Clear-cutting has been the dominant harvesting method used in boreal forest silviculture. Reducing the potential negative effects of intensive forestry activities on ecosystems, e.g., the simplification and homogenization of stand structure, requires diversifying silvicultural practices to promote forest resilience in the face of climate change. Priority therefore lies in developing, evaluating, and adapting partial cutting as a potential silvicultural option for ensuring the sustainable management of boreal forests. In this chapter, we summarize the findings of two large-scale experiments conducted in Canadian boreal forests that tested new silvicultural approaches and explore their implications for forest management. We discuss the effects of these treatments on tree growth, tree mortality, regeneration, and biodiversity, and we examine the challenges of existing silvicultural approaches in the context of climate change.

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16.1 Context

Ecosystem-based management (EBM) is a vehicle for achieving sustainable forest management and aims to balance ecological, social, and economic objectives (Franklin et al., 2018; Gauthier et al., 2008; Palik & D'Amato, 2017). EBM emerged from the natural disturbance emulation paradigm (Bergeron et al., 2001), in which silvicultural treatments are used to mimic the main disturbances and the natural range of variation of the ecological attributes of a forest area (Angelstam, 1998; Kuuluvainen et al., 2012; Fig. 16.1). In the boreal forest, natural disturbances such as fire, insect outbreaks, and windthrow are the driving forces that generate significant ecosystem changes at various spatial and temporal scales, depending on their frequency and severity and the size of the affected area (De Grandpré et al., 2000). These disturbance patterns determine the dynamics, structure, and composition of forests. Thus, silvicultural practices can simulate the composition and structure of post-disturbance forests by modifying stand attributes and producing variability within forest landscapes (Lecomte & Bergeron, 2005; Puettmann et al., 2015).

Over the past two decades, timber harvesting has become the main disturbance in boreal forest ecosystems. Currently, clear-cutting remains the main silvicultural treatment within the boreal biome, used within 83% of the harvested area in Canadian forests (Fig. 16.2; CCFM, 2018). Clear-cut systems offer the advantage of low costs relative to the harvested volume (Rosenvald & Lõhmus, 2008). The regeneration is assured either by plantation or by protecting the natural advanced regeneration (Groot et al., 2005). It is also used to simulate stand-replacing disturbances such as wildfires, i.e., high severity events affecting extensive areas, although clear-cut systems cannot fully mimic all postfire characteristics (Buddle et al., 2006). Although fire is the most

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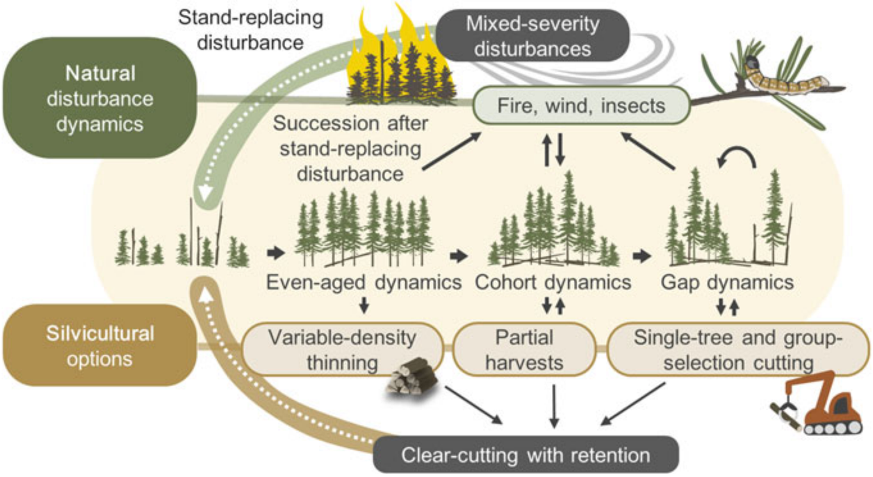

Fig. 16.1 This model represents silvicultural options for maintaining landscape-level forest structures and age distributions similar to those that would exist under a natural disturbance regime. Structural cohorts (*green bubbles*) correspond to the various postfire stand successional stages, and silvicultural options (*brown bubbles*) are presented along a gradient of harvest intensity. This illustration is inspired and adapted from the principle of the multicohort model and the ASIO model (Angelstam, 1998; Bergeron et al., 2002)

common disturbance in many boreal regions, this is not the case for all boreal forest landscapes. Consequently, forest management based entirely on clear-cut systems can alter structural and biodiversity characteristics at the stand and landscape scales (Bouchard & Pothier, 2011; Lindenmayer & Franklin, 2002). Consequently, even-aged management regimes having short forest rotations can produce habitat degradation, provoke the loss of productivity in some regions, and lead to structurally homogeneous stands (Fig. 16.2; Fischer & Lindenmayer, 2007; Nolet et al., 2018; Seedre et al., 2018). To address these concerns, forest management strategies in several boreal countries have prioritized the need to develop, diversify, and apply new silvicultural treatments within an EBM framework.

Partial-cutting treatments are a group of forestry practices included in existing boreal EBM strategies (Grenon et al., 2010). From an ecosystem management point of view, partial cuttings remove a portion of trees in a forest stand and maintain some characteristics of a closed forest cover (Fig. 16.2; Bose et al., 2014; Moussaoui et al., 2019). Partial cuttings that involve the removal of 30% to 50% of the stand basal area can therefore emulate natural disturbances of intermediate severity and extent, e.g., as observed following windstorms and insect outbreaks. Depending on management objectives, partial cutting is a generic term that can include commercial thinning (Nyland, 2016), selection cutting systems (Majcen, 1994), uniform and irregular shelterwood cutting systems (Raymond et al., 2009), HARP (harvesting with regeneration protection), and variable retention harvesting (Groot et al., 2005). Most of these treatments were initially developed in Europe and are being adapted

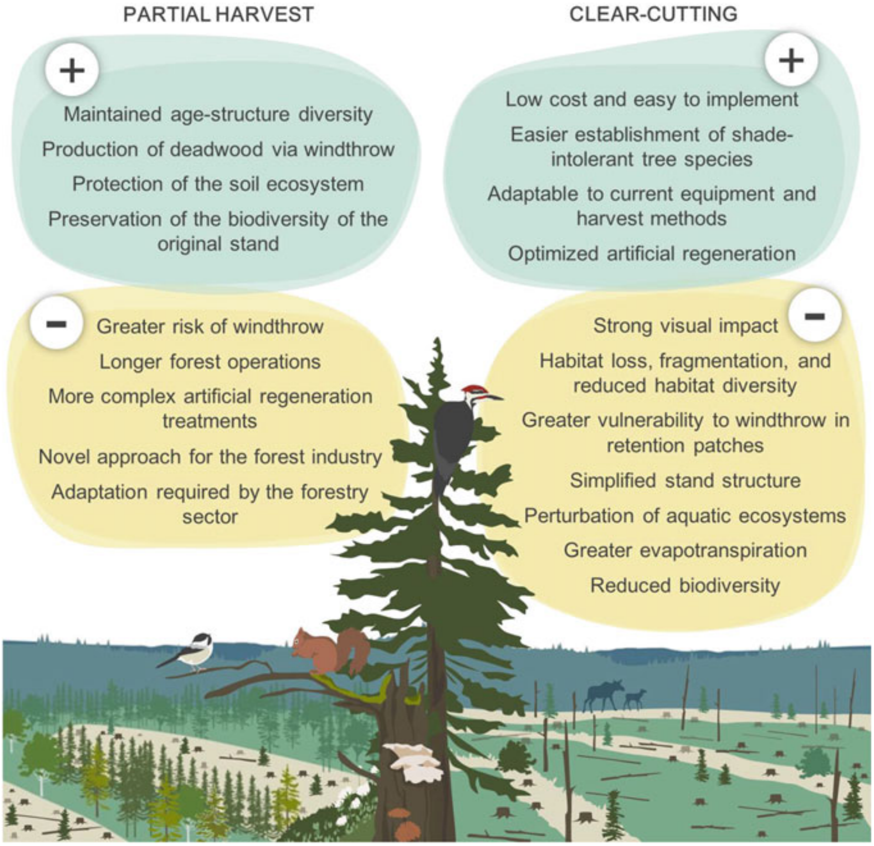

Fig. 16.2 Some of the potential advantages (+) and disadvantages (−) of using partial and clear-cutting harvests in the boreal forest. Clear-cutting is represented as it is applied in boreal eastern Canada, where harvest trails are restricted to less than 25% of the area to protect soils and advance regeneration

to the context of the North American boreal forest, in particular adjustments related to mechanized operations. This adaptation to new boreal contexts requires an understanding of the effects of partial cutting on residual tree growth and mortality, natural regeneration, and biodiversity before this approach can be considered as a tool for ensuring the sustainable management of boreal forests.

In this chapter, we synthesize observations from two large-scale experiments undertaken in the Canadian boreal forest, which assessed the short-, medium-, and long-term effects of various experimental partial-cutting treatments on stand growth, mortality, regeneration, and biodiversity. We then provide a perspective on future research directions and the implementation of these harvesting approaches in the Canadian boreal forest.

16.2 Large-Scale Experiments and Innovative Silviculture: Two Case Studies in Black Spruce Forests

The need to evaluate the silvicultural potential of partial cutting in Canadian boreal forests led to the establishment of two large-scale experiments within three forest regions in Québec, Canada (Saguenay, Côte-Nord [North Shore]): *MISA* (Managing innovative silvicultural alternatives) and RECPA (Réseau expérimental de coupes partielles en Abitibi) [*Abitibi partial cutting network]*. Both experiments comprise multiple replicates and long-term monitoring plots to investigate partial-cutting modalities adapted to mechanized operations in the black spruce (*Picea mariana* (Mill.) BSP)–dominated forests of Québec.

The MISA experiment, established by the Canadian Forest Service of Natural Resources Canada in 2003, involved three novel shelterwood treatments adapted to mechanized harvesting (Meek, 2006), standard clear-cutting, a seed-tree method, and untreated controls (Fig. 16.3; Montoro Girona et al., 2017). The shelterwood system aims to promote natural regeneration in the understory before a final harvest through the gradual opening of the canopy (Larouche et al., 2013; Matthews, 1991; Raymond et al., 2013; Smith et al., 1997). This approach maintains part of the residual stand as a seed source and as a means of offering partial shade to protect seedlings during the regeneration period and preventing the establishment of competing early-successional shade-intolerant species (Doucet et al., 1996; Raymond et al., 2000). Within an EBM context, shelterwood harvesting can be used to replicate the effect of a successional process occurring after low- to moderate-intensity secondary disturbances, such as insect outbreaks or windthrows, which promote the development of two-cohort stands (Drever et al., 2006; Kuuluvainen & Grenfell, 2012; Oliver & Larson, 1996; Smith et al., 1997). Incidentally, the shelterwood system allows residual trees to increase their volume before the final harvest and could be a promising silvicultural option for stands of black spruce—one of the most widely distributed species in North America (found from Québec to Alaska) and a shade-tolerant species that depends on exposed mineral soil for regeneration via seeds. Shelterwoods may provide an adequate solution for management strategies to maintain a high level of forest retention, particularly for the management of woodland caribou habitat (Courtois et al., 2004). This experiment was conducted in mature even-aged black spruce stands on upland sites, following a complete randomized block design with 36 experimental units of 3 ha each (Fig. 16.4).

The Abitibi partial cutting network (RECPA) was established in 1998 across northwestern Québec to test the operational feasibility of partial-cutting treatments in black spruce–feathermoss forests having an uneven-aged structure (Bescond et al., 2011; Fenton & Bergeron, 2007). RECPA included two experimental partial-cutting treatments: harvesting with advance regeneration protection (HARP) (Groot et al., 2005; Thorpe et al., 2007) and an experimental *conservation of canopy cover* (CCCC) treatment. This experiment also included clear-cut harvesting that removed

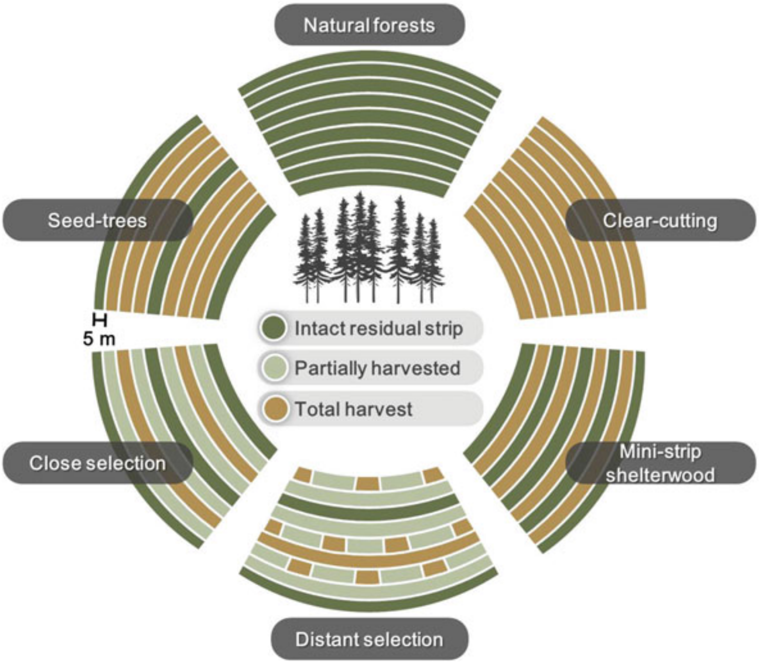

Fig. 16.3 Characteristics and spatial patterns of the three experimental shelterwood treatments and a seed-tree method applied in the MISA experiment

all merchantable stems (diameter at breast height; DBH > 9 cm). Both HARP and CCCC are applied to promote natural regeneration and stand growth. HARP is a partial-cutting treatment that involves removing stems with (generally) a DBH greater than 14 cm; this approach is used operationally in irregular boreal stands characterized by an abundance of saplings and small merchantable stems (Riopel et al., 2010). Moreover, HARP also promotes the development of both old-growth characteristics and the maintenance of high levels of biodiversity (Fenton et al., 2013; Opoku-Nyame et al., 2021). CCCC is a partial-cutting treatment in which stems from all diameter classes are harvested to maintain a similar proportion as that present before harvest (Arseneault et al., 2012). Although some partial-cutting treatments offer the potential of being effective at ensuring a regular input of deadwood and provide a compromise between conservation and harvesting in boreal forest stands (Fenton et al., 2013), some modalities, e.g., operational aspects, remain and affect the survival of residual stems. These modalities are insufficiently understood in the context of the Canadian boreal forest (Bose et al., 2014; Thorpe & Thomas, 2007). The RECPA experiment comprised six study sites, each site comprising three blocks (a partial cutting, clear-cutting, and untreated plot) of 50 ha each.

Fig. 16.4 **a** Naturally regenerating black spruce stand after clear-cutting, **b** partial cutting ten years post-treatment, **c** trail opening and canopy conditions after mini-strip shelterwood cuttings (50% removal). *Photo credits* Miguel Montoro Girona

16.3 Is Partial Cutting a Viable Alternative for Sustainable Forest Management?

16.3.1 Tree Growth

EBM aims to ensure both wood production and the maintenance of ecosystem functions. Thus, evaluating EBM performance must involve quantifying and understanding the effect of silvicultural treatments on tree growth. The effects of partial cutting on residual stand wood production in boreal forests are increasingly understood; several partial-cutting studies have been conducted involving various treatments and species in Scandinavia (Lähde et al., 2002; Pape, 1999; Peltola et al., 2002; Pukkala et al., 2009) and North America (Bourgeois et al., 2004; Goudiaby et al., 2012; Raulier et al., 2003; Schneider et al., 2008; Thorpe & Thomas, 2007). After partial cutting, residual stem growth generally increases because of decreased stand density and competition. For black spruce—the most harvested conifer in eastern Canadian forests owing to its excellent wood properties—residual stem growth depends on the partial-cutting intensity; the gain in tree growth is often marginal or insignificant for partial cuttings that involve about 30% of the basal area being removed, whereas marked residual stem growth is observed for cuts of 50% basal area (Goudiaby et al., 2012; Pamerleau-Couture et al., 2015; Soucy et al., 2012; Vincent et al., 2009). Normally, tree growth response is not consistent over time (i.e., the response is delayed by three to five years after treatment), across space (e.g., edge effect, site index and climate), and among stands (i.e., high individual tree variability related to ecological status, age, and genetics) (Montoro Girona et al., 2016, 2017).

In the MISA experiment, the novel shelterwood treatments enhanced the radial growth of black spruce stems, especially in younger stands (80–100 years old), and the growth response did not differ in relation to harvesting intensity or the type of silvicultural treatment applied among shelterwoods and seed trees. The radial growth response, 8 to 10 years postcutting, was 41% to 62% higher than that in untreated plots. The main factors affecting the growth response were stand structure, silvicultural treatment, tree position relative to skidding trails, growth before cutting, and time (Montoro Girona et al., 2016). Trees at the edge of the skidding trails showed twice the increase in growth compared with trees within residual strips, and this effect was greater in younger stands. Trail edges are characterized by less competition and a greater access to light and nutrients than within strips. On the other hand, trees located along trail edges may face greater exposure to wind and experience more frequent stem and root injuries caused by machinery during cutting and scarification operations than trees within strips (Cancino, 2005; Chen et al., 1993; Gardiner et al., 1997; Harper et al., 2016). In the MISA experiment, the positive response of black spruce along the trails suggests that the improved access to light and soil resources counterbalanced these potential trailside stresses (Fig. 16.5a). These observations confirm that silvicultural planning and stand selection in mature black spruce forests must consider both the spatial distribution of trails, to promote edge effect, and stand age, to maximize growth response.

In the RECPA experiment, residual stand volume showed net growth over the ten years that followed both the HARP and CCCC treatments in all studied sites (Moussaoui et al., 2020). Average tree-ring width after HARP in black spruce stands was double that of preharvest stands (Thorpe et al., 2007). In uneven-aged black spruce–dominated stands, greater tree radial growth after partial cutting can be limited by tree age and intertree competition (Pamerleau-Couture et al., 2015). In uneven-aged black spruce stands, although heavy partial cutting can re-attain the preharvest basal area 45 years after harvest (Groot, 2014), this return to the initial basal area can take 65 to 105 years on poorer quality sites corresponding to a more limited establishment of post-harvest growing stock (Thorpe et al., 2010). In Québec, HARP tends to reduce forest rotation. Results obtained 20 years post-treatment in the HARP experiment indicate that this reduction in forest rotation could be 40 to 50 years for stands having a median forest rotation of 80 to 90 years. This finding suggests, therefore, that in

Fig. 16.5 Response of black spruce stands after experimental silvicultural treatments in MISA; **a** tree rings show the strong radial growth response of edge trees during the first ten years after treatment; **b** windthrow damage observed ten years after the seed-tree method; **c** black spruce seedlings established ten years after the experimental shelterwood and scarification. *Photo credits* Miguel Montoro Girona

terms of residual tree growth, by considering site quality, partial-cutting treatments had a positive effect to promote radial growth after cutting.

16.3.2 Post-Harvest Mortality and Windthrow

A significant risk associated with partial cutting is post-harvest mortality due to windthrow disturbance (Fig. 16.5b). Partial cutting increases wind penetration into the residual stand, heightening the risk of windthrow (Gardiner, 1995; Riopel et al., 2010; Ruel, 1995). This effect is most evident during the first five years post-treatment (Jönsson et al., 2007; Macisaac & Krygier, 2009; Ruel, 2000; Thorpe et al., 2008) or where wind exposure is increased by large nearby openings or wind-favoring topography. Factors influencing windthrow include wind exposure (Ruel, 2000; Scott & Mitchell, 2005), edaphic conditions (Mitchell, 1995; Ruel, 1995; Stokes et al., 1995), stand composition (Burns & Honkala, 1990; Raymond et al., 2000; Riopel et al., 2010), stand density (Cremer et al., 1982; Maccurrach, 1991), as well as stem mass, size, and height/diameter ratio (Riopel et al., 2010). In addition, tree injuries incurred during harvest operations may contribute to increase mortality for stems located next to skid trails (Bladon et al., 2008; Thorpe et al., 2008).

In the MISA experiment, 76% of the post-harvest mortality, ten years after treatment, could be explained by harvest treatment, machinery-caused injuries, and distance to adjacent cuts (Montoro Girona et al., 2019). Windthrow accounted for 80% of post-harvest mortality. Therefore, an expected increase in mortality with greater harvest intensity must be included in silvicultural guidelines for applying uniform shelterwood treatments and seed-tree harvesting (e.g., see Stathers et al., 1994). Retention levels should aim at 45% to 65% of the initial basal area to minimize losses, and stand selection should prioritize sites having conditions that favor the lowest probability of windthrow. Moreover, low retention levels increase the risk of tree mortality and produce high overturn rates, thereby compromising silvicultural objectives (Urgenson et al., 2013).

The success of partial cutting depends mainly on the survival of residual trees. Ten years after harvest, the uniform shelterwood treatments tested in the MISA experiment resulted in a mortality that was 15% to 20% higher than that observed in the control stands; however, this mortality was still within the range of that observed in natural stands in this area (De Grandpré et al., 2008). In the MISA experiment, seed-tree harvesting experienced the highest levels of mortality (45%–75% of the residual stems), primarily because of the higher exposure of residual trees to wind, relative to uniform shelterwood treatments, in which only trees along the trails and the edges close to clear-cut areas were highly exposed. Trees along smaller and more exposed residual strips are more vulnerable to wind damage (Jönsson et al., 2007) and experience higher rates of overturn in residual stands (Achim et al., 2005). Anyomi and Ruel (2015) and Urgenson et al. (2013) observed similar patterns, finding that high harvest intensity, such as that using seed trees and the removal of 75% of the basal area, produced 60% to 80% post-harvest mortality; these levels correspond to twice the amount of windthrow than that observed for intermediate intensity harvesting (40%–60% removal)—levels removed in the shelterwood system, for example.

Much of the research conducted in the RECPA experiment focused on the impacts of partial cutting on residual tree mortality over the short, medium, and long term (Lavoie et al., 2012). Moussaoui et al. (2020) demonstrated that ten years post-harvest, stem losses in black spruce forests depend largely on preharvest stand structures and site conditions, in agreement with previous results coniferous-dominated stands (Riopel et al., 2010). Moreover, the RECPA experiment showed that ten years after harvesting, depending on harvest treatment intensity, partial cutting could increase post-harvest tree recruitment and growth or reduce stand basal area because of a high rate of standing tree mortality (Moussaoui et al., 2020). For example, no cases of high mortality (basal area occupied by dead trees) were observed ten years after harvest when treatment intensity (HARP or CCCC), i.e., the percentage of harvested basal area, was $\leq$48%. In a study comparing mortality after dispersed and group-retention partial cuttings in Canadian boreal forests, Lavoie et al. (2012) observed that increased wind penetration into residual stands heightened post-harvest mortality; a combination of factors likely caused this increase, including fine-textured soils, flat topography, and the dominance of shade-intolerant species. Moussaoui et al. (2020) suggest that partial cutting in black spruce forests should be avoided in sites where the organic layer thickness approaches 17 cm or more to ensure an increase in the decennial stand yield after harvesting. From the results of both experiments, post-harvest tree mortality in boreal forests can be predicted using pre-existing stand conditions, even before considering the influence of the intensity and configuration of a partial-cutting treatment. Understanding the factors involved in this complex phenomenon is important for reducing post-harvest losses.

16.3.3 Regeneration

Successful natural regeneration is fundamental to sustainable forest management, as it enables the resilience of forest ecosystems. Natural regeneration is central to most management strategies in the boreal biome (Bose et al., 2014; Kuuluvainen, 1994; McDonald & Urban, 2004; Messier et al., 1999; Prévost, 1996; Prévost et al., 2010). Natural regeneration of boreal forests involves numerous processes, including seed production and dispersal, germination rates, seedling establishment, and early seedling and sapling growth and mortality (Blanco et al., 2009; Thiffault et al., 2015). Stand structure and silvicultural treatment determine ecological factors such as light availability, and substrate influences the quality of the environment for seedling establishment and growth. The availability and distribution of seedbeds composed of exposed mineral soil are crucial elements for the successful regeneration of boreal stands (Kolabinski, 1991; Martin et al., 2020; Raymond et al., 2000). Moreover, new openings in the forest cover caused by partial cuttings alter light availability and the physical conditions in the forest and its understory (Barik et al., 1992; Coates, 2000, 2002; Parent & Messier, 1995). Numerous studies have examined the role of increased light availability on the understory (Beaudet et al., 2011; Canham et al., 1990; Chazdon, 1988) and its effect on the growth of regenerating trees (Beaudet & Messier, 1998; Kobe et al., 1995). Studies have also quantified the influence of opening size on cohort biomass (Webster & Lorimer, 2002), variations in canopy openings after partial cutting (Beaudet & Messier, 2002; Domke et al., 2007), and gap formation rates (Raymond et al., 2006; Runkle, 2000; Van Der Meer & Bongers, 1996).

The MISA experiment evaluated how the creation of canopy openings from the uniform shelterwood treatments affected the density, stocking, and size of black spruce seedlings after partial cutting (Fig. 16.5c; Montoro Girona et al., 2018). The experiment demonstrated that uniform shelterwood and seed-tree treatments produced an abundant regeneration of black spruce seedlings and provided a more effective silvicultural option than clear-cutting in that regard; for example, experimental shelterwood-treated stands produced three times more regeneration outcomes than that observed in clear-cut stands (Montoro Girona et al., 2018). The shelterwood treatment involving a series of narrow cut strips (mini-strip shelterwood) was the most effective in terms of regeneration stocking after ten years. The MISA results indicated that regeneration outcomes depend more on substrate than light during the first ten years post-harvest. Following partial cutting, all sites were scarified using a 10-ton excavator equipped with a 1 m^3 bucket in the skidding trails and along their edges where the residual spacing of trees allowed. Scarification promoted the stocking and density of black spruce regeneration by exposing the mineral soil, thereby emulating the effects of fire on the organic layer. Thus, partial cutting combined with patch scarification created the required substrate (mineral soil) and light conditions (lateral shadowing from the residual strip) to promote black spruce regeneration. No major competition with deciduous trees and shrubs was observed; however, future research must be undertaken to measure the changes over the longer term.

Piché (2017) described the effects of partial cutting on regeneration establishment ten years after treatments within the REPCA experiments. Stocking was similar between partial-cutting and clear-cutting treatments, whereas seedling growth remained low on paludified sites. The regional climate and physical characteristics of the soils found in the Clay Belt region of eastern Canada favor the accumulation of organic matter and the rise of the local water table (Bescond et al., 2011; Fenton et al., 2005, 2009; Payette & Rochefort, 2001). Moreover, the anchoring and intertwining of black spruce root systems is reduced; this leads to decreased natural establishment and productivity (Lafleur et al., 2010; Lecomte et al., 2009). Understanding the forest dynamics of this region and adapting partial-cutting modalities will require further studies, particularly in forest stands prone to paludification. Furthermore, the recent assessment of the effects of partial cutting ten years after treatment on stand development (recruitment, growth, and mortality) in RECPA stands revealed that tree recruitment increases significantly with greater residual sapling density. Moussaoui et al. (2020) found that a minimum density of 800 saplings/ha appears sufficient to promote the healthy recovery of black spruce stands and a high stand yield after partial cutting. Therefore, black spruce stands having a diversified diametrical structure with an abundance of saplings will respond positively to partial cutting over the short term.

16.3.4 Biodiversity

Silvicultural treatments modify the biotic (e.g., species composition, diversity, and community structure) and abiotic (e.g., light availability, soil temperature, and water availability) environment of forest stands (Kim et al., 2021). The effects of soil disturbance on vegetation colonization are site specific and depend largely on disturbance size and intensity, preharvest species composition, and species' functional traits. Seedbed conditions and existing seed banks also significantly influence shrub colonization following soil disturbance, as illustrated in multiple successional studies (Lafleur et al., 2010, 2015; Lecomte et al., 2006; Prévost, 1996).

Understory vegetation is a good indicator for understanding changes in forest dynamics caused by silviculture, as it is directly influenced by the dominant tree cover (Fraver et al., 2007; Hernández-Rodríguez et al., 2021; Macdonald & Fenniak, 2007). Previous studies in western Canada have focused on the response of plant communities after a clear-cutting of mixedwood forests in Manitoba (Kembel et al., 2008) and partial cutting in Alberta (Caners et al., 2013) and British Columbia (Man et al., 2010). In eastern Canada, forest succession after partial cutting has been studied in maple (*Acer saccharum* Marsh)-dominated stands (Archambault et al., 2003), mixed yellow birch (*Betula alleghaniensis* Britt.)–balsam fir (*Abies balsamea* (L.) Mill.) forests (Dubois et al., 2006), balsam fir–dominated stands (Raymond et al., 2000), and black spruce–dominated ecosystems (Fenton et al., 2013).

In the RECPA experiment, much of the research has focused on the impacts of partial cutting on biodiversity (Bescond et al., 2011; Fenton & Bergeron, 2007; Fenton et al., 2013; Paradis & Work, 2011). Partial cutting at a minimum of 40% to 60% retention maintained habitat attributes for various organisms (Bose et al., 2014; Fenton et al., 2013). Species-specific responses to partial cutting can be positive for both understory plants (Bescond et al., 2011) and small mammal populations (Cheveau et al., 2004), which are relatively resilient to low retention levels (<40%). Similar benefits were documented for vascular plants and mosses (Arseneault et al., 2012; Bescond et al., 2011; Fenton & Bergeron, 2007; Opoku-Nyame et al., 2021), epiphytic lichens (Boudreault et al., 2002), and birds (Lycke-Poulin, 2008) in the RECPA experiment. Maintaining arthropod assemblages similar to those of older, unmanaged forests requires, however, higher retention levels (>60%; Jacobs & Work, 2012; Paradis & Work, 2011). In the context of EBM, findings from the RECPA experiment for a variety of species groups indicate that a 50% retention level appears appropriate for maintaining biodiversity; however, long-term monitoring is required to inform adaptation strategies for sustainably managing forests in the context of a changing climate, as well as to include the larger body size species to improve our understanding of the biodiversity patterns at the landscape scale for different structural stands.

16.4 Research Perspectives

In this chapter, we have addressed some critical aspects of novel silvicultural treatments that aim to promote residual tree growth, minimize windthrow damage, favor regeneration, and maintain biodiversity in the boreal forest. Although we have focused on the MISA and RECPA experiments, other large-scale experiments, such as EMEND (Spence et al., 1999), SAFE (Brais et al., 2004), and EVO (Vanha-Majamaa et al., 2007), provide invaluable insights into alternative management systems applicable to the boreal forest. Nonetheless, a more complete assessment of sustainable forest management in the context of climate change requires additional research on a number of fronts:

Economic implications The selection and application of silvicultural treatments are highly dependent on financial and economic profitability. Future work should include analyses of the cost/benefit ratios related to implementing partial cutting in the boreal context and develop cost-effective means of planning, conducting, and monitoring partial-cutting treatments on an operational basis. Finally, the impact of partial cuttings on wood quality and value must be addressed to analyze final product values in the wood market.

Long-term monitoring of growth and yield Climate change will alter the growth dynamics of stands and species; new estimates of optimal rotations will probably be required. Large-scale experimental designs comprising permanent sampling plots offer the opportunity for a long-term monitoring of tree growth and stand dynamics (e.g., Achim et al., 2021; Pappas et al., 2022; Thiffault et al., 2021). Further investigations of the growth response in black spruce stands after partial cutting should examine the extent (distance) of the edge effect along residual strips; such research would help maximize post-treatment wood production. Another pressing question concerns the full estimate of postcutting growth response over time. Currently, existing dendrochronological series of black spruce from postcutting growth studies do not exceed 12 years (Montoro Girona et al., 2016, 2017; Pamerleau-Couture et al., 2015; Thorpe et al., 2007); longer-term assessments are required for planning the timing of the final cut and optimizing the effect of the treatment on radial growth.

Forest regeneration under climate change As climate change will lead to altered precipitation and temperature patterns and likely favor more frequent summer drought periods. Partial cutting could help reduce seedling vulnerability to drought; however, no studies have addressed this question to date. Climate change will create novel stand compositions, and the greater presence of hardwoods in boreal forest stands must be addressed (Brumelis & Carleton, 1988; Riopel et al., 2011; Solarik et al., 2020). The opening of the canopy, for example, stimulates the germination and survival of paper birch (*Betula papyrifera* Marsh.) (Perala & Alm, 1990). Even if hardwood species are generally found in relatively open areas receiving higher irradiance, some species can survive for a few years under conditions of 10% sunlight (Messier et al., 1999). Thus, early regeneration in unmanaged boreal forests characterized by infrequent fires is dominated by more shade-tolerant softwood species. Deciduous competition could affect the growth of black spruce seedlings and thus requires a careful analysis of regeneration after partial cutting.

Insect outbreaks Climate change is shifting spruce budworm (*Choristoneura fumiferana* (Clemens)) habitats to a more northern range and into areas currently dominated by black spruce (Navarro et al., 2018). Because of the potential significant impacts of spruce budworm outbreaks on residual stands and the postcutting regeneration, it is necessary to understand the spruce budworm–related effects in interaction with novel silvicultural practices. Between 1990 and 2016, harvesting affected 24 million ha in Canada. Consequently, a large portion of the North American boreal forest exists at an early development stage; it is thus important to understand the vulnerability of regeneration after cutting to insect outbreaks (Cotton-Gagnon et al., 2018; Lavoie et al., 2019). A recent study has demonstrated that partial cuttings can reduce the impact of insect outbreaks on regeneration (Lavoie et al., 2021); however, much more research is required to better understand these insect-regeneration interactions under future climate change.

Windthrow Climate change projections indicate increasing windthrow and wind damage in forests will significantly impact stand dynamics in the near future (Saad et al., 2017). Pursuing the research efforts conducted over the last 20 years (Achim et al., 2005; Gardiner et al., 2008; Solarik et al., 2012) is essential to understand better the factors driving forest vulnerability to wind damage, especially following partial cutting. These studies would contribute to minimizing the uncertainties associated with climate change in forest management strategies and help create decision support tools that consider those risks in planning. Finally, management measures that reduce windthrow risk must be tested further to provide effective tools for silviculturists in preventing losses due to wind damage.

Carbon sequestration Increasing the C sequestration capacity of a forest requires an understanding of the effects of management and climate together with predictions as to how these effects might change in forest ecosystems over both the short and long term (Hof et al., 2021). Silvicultural treatments and systems could create or maintain stands of suitable structure and composition to promote C sequestration and mitigate and adapt ecosystems to the effects of global change (Paradis et al., 2019). Partial cutting with cut-to-length or tree-length harvesting systems has been identified as a potential solution for increasing biomass and soil C content (Ameray et al., 2021); however, the long-term effects are not fully understood, particularly in terms of the modality and the intensity of partial cutting.

16.5 Conclusions

The large-scale experiments presented in this chapter are essential for quantifying the multiple ecological and economic outcomes of forest management alternatives. From the existing data, partial cutting offers viable silvicultural alternatives to clear-cutting when required by sustainable forest management objectives. The experimental treatments reviewed here promote residual tree growth, reduce windthrow-related losses, favor regeneration, and help maintain biodiversity. Nonetheless, the clear-cut system remains the main silvicultural regime within the boreal biome. Although it is an appropriate approach in many contexts, clear-cutting can create fragmented landscapes, promote young and even-aged stands to the detriment of multi-cohort stand structures, and benefit some commercial species rather than ensuring a more diverse composition. Moreover, current even-aged management tends to reduce forest structural variability. A more diverse silviculture that integrates partial cutting into the portfolio of available treatments could increase forests' adaptive capacity and resilience in the face of climate change, allowing to maintain a larger spectrum of forest composition and structures at different scales across the landscape.

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