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Forest Management and Climate Change: Adaptive Measures for the Temperate–Boreal Interface of Eastern North America

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20.1 Introduction

The forests cover about 30% (4 billion ha) of the Earth's continental surfaces (FAO 2010; Lindquist et al. 2012), 17% of which are in North America (Cohen and Miller 2001). There are four main forest biomes on the planet. Among these, the deciduous temperate forest biome covers 1.04 billion ha (Fischlin et al. 2007). The boreal biome covers 1.27 billion ha (33% of the planet's forested surfaces) and constitutes the second largest forest biome in the world after the tropical forests, which cover 1.75 billion ha (Fischlin et al. 2007, 2009). This biome extends primarily to Canada, Alaska, Fennoscandia, and Russia (FAO 2001, Fischlin et al. 2007, 2009) and beyond the polar circle in some countries. This is the forest biome with the lowest average annual temperatures and the lowest number of tree species (Fischlin et al. 2009).

These two biomes are present alongside one another, both in Eurasia and in America, where they support a sustained silvicultural activity (Amiro et al. 2006; Fischlin et al. 2009). For the boreal forest only, about 600 million m^3 of wood is harvested annually, which corresponds to 20% of the planet's entire harvest (Fischlin et al. 2009). For the boreal and temperate forests, this proportion should increase by 25% by 2030 (Turner et al. 2006). Between 2005 and 2010, the total C stored in the world's forests has decreased by 0.5 gigaton (Gt) annually (FAO 2010), mostly due to human activities, that is, forest exploitation and forest clearance for agriculture (Heimann 2008). The C sequestration function of forest ecosystems is a major component of the terrestrial C balance that is highly influenced by natural disturbances and forest management.

20.1.1 Climate–Forest Relations

Climate influences forests and forests influence the climate on a global and on a regional scale. The Holocene/Anthropocene global warming is the major cause of the northern migration of tree species that had taken refuge south of the continental ice cap (MacDonald 1993; King and Herstrom 1997; McLachlan et al. 2005). Species would have moved northward at a pace of 10–50 km century^{-1} (McLachlan et al. 2005; Feurdean et al. 2013) to form the forests of the temperate and boreal biomes, with early-successional species migrating more rapidly than late-successional species (Feurdean et al. 2013). The global warming of 0.6°C in 30 years (Hansen et al. 2006) is much more rapid than the one of 0.6°C between 11,300 and 9,500 BP during the Holocene (Marcott et al. 2013); accordingly, the current and future northern migration rate of tree species should occur faster than the one observed during the Holocene so that species can follow the displacement of their thermal zone (Feurdean et al. 2013).

The current geographical distribution of tree species, along with regional climate patterns, allows for the delimitation of zones that are defined by macroclimatic conditions and assemblages of relatively homogeneous species, variably designated under terms such as ecoregions (Bailey 1980), ecozones (MRNF 2009), and forest provinces (Bailey 1980). From south to north of the temperate–boreal interface in eastern North America, there is a succession pattern of these types of zones. In the northeastern United States and southeastern Canadian forests, species such as white pine, hickories, oaks, and maples are found (Bailey 1980; Burns et Honkala 1990a,b). Annual average temperatures are between 16°C and 6°C and precipitations are at least 500 mm (Walter 1979). Progressing toward the north, the balsam fir zone and then the spruce zone with more boreal species, such as balsam fir, spruces, poplars, and birches, are observed. Annual average temperatures vary from 5°C to −5°C and there is a precipitation gradient from 1300 mm in the balsam fir zone to 300 mm in the more northerly spruce zone (Fischlin et al. 2009).

The role of forests in climate regulation has just recently been recognized (Cohen et Miller 2001; Bonan 2002; Seppälä et al. 2009), notably in context with the interest in the global C cycle (Rollinson 2008; Lindquist et al. 2012). Globally, the planet's forests constitute a 1200 GtC reservoir, including the C from the soil comparatively to 762 GtC for the whole atmosphere (Dixon et al. 1994; Freer-Smith et al. 2008; Rollinson 2008). Boreal forests account for more than 30% of the planet's C (Post et al. 1982; Manies et al. 2005; Symon et al. 2005) and 13% of all the C contained in forests (Jobbagy and Jackson 2000), with 20% as living biomass and 80% stored in woody debris, litter, and organic C in the soil (Melillo et al. 1990; Dixon et al. 1994; Goulden et al. 1998; Apps et al. 1999). Meanwhile, temperate deciduous forests store 14% (168 GtC) of the C of all forest biomes from around the world (Dixon et al. 1994). During the growth process, the C sequestration rate can vary from 1 to 26 tons of CO_2 ha^{-1} year^{-1}, depending on the site's productivity (Fensham and Guymer 2009); about a third of this amount is transported to the root system to be used in respiration and root growth or to be lost to the soil (Norby and Jackson 2000).

The influence of forests on climate is closely related to their successional status and to the disturbance regime. Following a severe disturbance at the local scale, forests become a C source because the decomposition of organic matter emits more C than the amount sequestrated in tree growth (Kirschbaum 2000; Seppälä 2008). Of the 40 GtC from human origin emitted annually in the atmosphere (Lemprière et al. 2008), 5.9 GtC comes from surface areas exploited for timber production and agriculture (Heimann 2008). This trend is progressing because 60,000 km^2 year^{-1} of forest areas is modified by industrial activities, primarily by forest exploitation (FAO 2010). At the same time, the net surface area of global forests decreased by 1.7% between 1990 and 2005 (Lindquist et al. 2012). Between 1920 and 1980, the boreal forest of Canada was a C sink (Kurz and Apps 1999), but several natural disturbances by insects and fires have reduced the C stock accumulated in the Canadian forest for more than half between 1990 and 2007, the largest decline among forest biomes of the world (Pan et al. 2011). Forest practices associated with even-aged management (Box 20.1), in single or few species stands, also have a significant impact on C balance on a large scale because of the types of logging practices, the area of harvested surfaces, and the intervals between them (Hunter 1999; Drever et al. 2006; Taylor et al. 2008; Innes et al. 2009; Lucier et al. 2009; Coursolle et al. 2012). Because of the associated greenhouse gas emissions, classic silvicultural practices may prove to be a catalyst for ongoing climate change (Taylor et al. 2008; Nunery and Keeton 2010). By comparison, the changeover from an even-aged to an uneven-aged management regime in the boreal forest biome could store up to 6% more CO_2 over a period of 140 years (Taylor et al. 2008) and up to 100% over a longer period in the boreal forest and deciduous temperate biome (Harmon et al. 2009; Nunery and Keeton 2010). Silvicultural practices that aim to maintain a permanent cover with frequent partial cuts promote long-term C sequestration capacity higher than unmanaged forest or forestry approach clearcutting practices (Harmon et al. 2009). If adaptation measures are applied, the sequestration potential from the planet's forest ecosystems is evaluated to 4 Pg C year^{-1}, while currently it is 1.1 Pg C year^{-1} (Settele et al. 2014). This chapter proposes proactive silvicultural adaptation measures that could substantially contribute to reaching goals in the overall reduction of greenhouse gases emissions and that are applicable at the landscape and stand levels. These measures are mainly proposed to forest managers and foresters of the temperate–boreal interface of northeastern North America.

BOX 20.1 EVEN-AGED AND UNEVEN-AGED SILVICULTURAL REGIMES

The forest stands can be managed in order to get or maintain an even-aged or an uneven-aged structure (Schütz 1997). At the temperate-boreal forest interface, the even-aged forest management regime is mainly applied in stands dominated by short-living species such as balsam fir and intolerant hardwood. The even-aged management regime can also be applied in plantations of long-living softwood when the objective is essentially timber production. The silvicultural sequence usually involves a thinning in the case of naturally occurring stands and two or even three commercial thinnings in the case of plantations. The final step of this silvicultural regime is generally clearcutting.

The uneven-aged management regime is primarily applied in natural stands or plantations with a component of long-living species such as spruces, northern white-cedar, sugar maples, oaks, ash, bitternut hickory, black walnut, butternut, and black cherry. This silvicultural regime can be implemented from an even-aged stand where two or three commercial thinnings are performed prior to irregular shelterwood cuts that keep permanent cover. This is the type of silvicultural system for creating more complex structures compared to an even-aged forest management plan (O'Hara and Ramage 2013).

20.2 Impacts of Climate Change on Forest Dynamics

Global warming should increase the impact of climate-related disruptive agents. In certain regions, we expect longer droughts, fires that are more severe and more frequent (Flannigan et al. 2005a,b; Bond-Lamberty et al. 2009; Allen et al. 2010), more violent wind episodes, and more devastating ice storms (Johnston et al. 2010). Insect infestations and diseases should be more severe, especially if the hosts are abundant, vulnerable to climate change, and located at the limit of their range of distribution (Volney and Fleming 2000; Johnston et al. 2010) and if they form forests with low tree species diversity (Moreau et al. 2006; Jactel and Brockerkoff 2007).

Temperature, CO_2 concentration, light, water, and access to nutrients constitute limiting factors of prime importance to the productivity of forests (Price et al. 1999; Boisvenue and Running 2006; Karnosky et al. 2008). An increase in global average temperature of 4°C by 2100 could lead to a northern movement of isotherms 500 km in the Northern Hemisphere (Thuiller 2007). Most models predict that a warmer climate will lead to increased productivity in temperate (Alcamo et al. 2007; Field et al. 2007; Alo and Wang 2008) and boreal (Fischlin et al. 2007; Kurz et al. 2008; Fischlin et al. 2009) forests and certain empirical studies confirm this trend (Pretzsch et al. 2014). Productivity has a direct link with C accumulation at the stand level (Man et al. 2013; Schütz and Pommerening 2013). C accumulation appears to be linked to species and to drought conditions prevailing during or before the growth period (Barr et al. 2004; Boisvenue and Running 2006; Fischlin et al. 2009; Huang et al. 2010; Lloyd et al. 2013). However, the productivity increase associated with the lengthening of the growth season could be canceled due to longer drought periods (Kirschbaum 2000; Barr et al. 2004; Kirschbaum 2004; Boisvenue and Running 2006; Huang et al. 2010), particularly in the central part of the North American boreal forest (Meehl et al. 2007; Fischlin et al. 2009; Girardin et al. 2009).

The geographical position, the tree species diversity, and the current extent of each ecological unit might be altered in the course of the present century (Malcolm et al. 2002; McKenney et al. 2007; Iverson et al. 2008; Allen et al. 2010; Chambers et al. 2013; Duveneck et al. 2014). The planet's global warming should provoke a northern migration and a southern decline for some species (McLachlan et al. 2005; Fischlin et al. 2007). The northern migration of species at the same rate than the northern displacement of isotherms induced by an increase in temperature of 4°C by 2100 would result in a displacement rate of 5 km $year^{-1}$, which is 10 times faster than what was observed during the Holocene. A rapid and sustained warming of annual average temperatures may cause phenological changes in species, which will make them more vulnerable to disruptive agents (Colombo 2008) and less able to regenerate naturally (Chambers et al. 2013; Fisichelli et al. 2013a,b). It is expected that temperate and boreal forests will be particularly affected by the ecosystem disturbances caused by global warming because temperature increase is greater in these regions and more particularly in the boreal forests (Plummer et al. 2006; Christensen et al. 2007; Colombo 2008; Lemmen et al. 2008; Fischlin et al. 2009; Lucier et al. 2009). For example, by the end of this century, in the northeastern United States and neighboring regions of Canada, a decline in conifer species, such as fir and spruces, and their gradual replacement by hardwood species, such as oaks, maples, and hickories, is expected (Iverson et al. 2008). Therefore, most of the balsam fir zone will become within a few decades a sensitive forest region and the lack of proactive adaptation measures may reduce the productivity of these ecosystems (Duveneck et al. 2014).

20.3 Adapted Forest Management

Although the effects of global warming on forest ecosystems have been measured in the last few decades (Boisvenue and Running 2006; Johnston et al. 2006; Innes et al. 2009), the development of a silviculture adapted to this phenomenon is only beginning (Spittlehouse 2005; Innes et al. 2009; Magruder et al. 2013). Adapted forest management enhances forest productivity and resilience (Folke et al. 2004; Spittlehouse 2005), which in turn improve their capacity to sequester C originating from the use of fossil fuel. The design of adapted silvicultural approaches will be inspired by new emerging practices focused on

1. Ecosystem-based forest management (Hunter 1996; Bergeron et al. 1999; Gauthier et al. 2008; Vaillancourt et al. 2008)
2. The complex structure principle (Steenberg et al. 2011; Puettmann 2011; Buongiorno et al. 2012; Schütz and Pommerening 2013)
3. Species diversity (Cavard et al. 2010; Schütz et al. 2012; O'Hara and Ramage 2013; Puettmann and Tappeiner 2014)
4. Adaptability by genetic diversity (Stokes and Kerr 2009; Kuparinen et al. 2010; Küchli 2013)

The use of an uneven-aged silviculture in mixed-species stands is presently imposing itself as the most favorable silvicultural regime since it allows for increased adaptation capacities to changes in water and thermal regime induced by global warming (Evans and Perschel 2009) and would have positive effects on C accumulation compared to even-aged management (Seidl et al. 2007; Taylor et al. 2008) or unmanaged stands (Harmon et al. 2009).

The general principle/objective of silvicultural adaptation measures to global warming should be the maintenance or increase of C sequestration by the forest ecosystem (Drever et al. 2006; Vallet 2008; Bradford and Kastendick 2010; Liu et al. 2011; Wang et al. 2013). These measures are notably based on the following:

1. The reforestation of abandoned farmlands and of poorly regenerated forested areas (Harmon and Marks 2002; Spittlehouse and Stewart 2003; Anderson et al. 2006; Foote and Grogan 2010; Tremblay and Ouimet 2013)
2. The implementation of partial cuts (or selective felling) in order to maintain optimal microclimatic conditions (Brassard and Chen 2010; Horner et al. 2010; Magruder et al. 2013) favorable to growth (Sohn et al. 2013) and the natural regeneration of adapted tree species (Fisichelli et al. 2013a,b)
3. The creation of seedbeds suitable for establishing regeneration (Fisichelli et al. 2013a,b)
4. The control of the size and frequency of clearcuts (Brassard and Chen 2010) to move toward a stable age structure at the landscape scale (Pregitzer and Euskirchen 2004; Magnani et al. 2007; Bradford and Kastendick 2010), given the longevity of the tree species and vulnerability of the stands (Wang et al. 2013)
5. The restoration of a small gap regime to establish a regeneration of adapted and rarefied tree species (O'Hara 2001; Fahey and Puettmann 2007; Franklin et al. 2007)
6. The structural conversion of regular stands toward uneven-aged/irregular ones to restore a structural, floristic (Puettmann 2011; Schütz and Pommerening 2013; Puettmann and Tappeiner 2014), and genetic complexity (Stokes and Kerr 2009; Küchli 2013)

20.4 Adaptation Measures at the Regional and Landscape Scales

Current policies that govern forest management worldwide remain primarily focused on the production of woody material (Puettmann and Tappeiner 2014), which leaves the practitioner few silvicultural options specifically designed to prepare forests for ongoing climate change (Macdonald et al. 2010; Patry et al. 2013). In western Canada, a few approaches have been initiated to integrate new practices adapted to climate change. For example, adaptation measures have been included in management plans, such as assisted migration and forest logging management, to decrease the risks of fires (Yamasaki et al. 2008) or epidemics (Johnston et al. 2006).

In addition to assisted migration, control of the age structure, reforestation of abandoned farmlands, and poorly regenerated forested sectors are other examples of adaptation measures to climate change applicable at a large scale. Forest landscapes composed predominantly of stands aged between 30 and 120 years should display a positive C balance (Pregitzer and Euskirchen 2004; Magnani et al. 2007), whereas surface areas in regeneration should be minimized (Pregitzer and Euskirchen 2004; Coursolle et al. 2012; Tremblay and Ouimet 2013) along with areas of poorly productive stands that represent a C source (Pregitzer and Euskirchen 2004). Even if old forests represent a C source, their role is to store very large amounts of C over a long period (Kurz and Apps 1999; Harmon and Marks 2002; Pregitzer and Euskirchen 2004), hence the importance in conserving them. The choice of a silvicultural regime, either even-aged, uneven-aged, or both at the same time, will depend on the natural disturbance regime for a given region. For example, in regions where large-scale, stand-replacing natural disturbances dominate, or where the fire cycle would be less than 100 years, the even-aged silvicultural regime might be suitable because after large-scale disturbance natural regeneration will result in even-aged stand in any event (Etheridge and Kayahara 2013). However, in regions dominated by secondary natural disturbances of medium and small sizes (<10 ha) with long intervals (150 years and more) such as insect attacks, storms, or windthrow, the uneven-aged regime should be favored (Harvey et al. 2002; Etheridge and Kayahara 2013). In addition to these two alternatives, a mixed situation could be well suited in a region where the entire range of natural disturbances is represented. In such situations, both silvicultural regimes can be applied in concomitance and could constitute the best orientation to take in most regions of northeastern North America.

The reforestation of abandoned farmlands represents another adaptation measure at the regional and landscape levels. Several regions of eastern North America were affected by the rapid expansion of agricultural lands in the early 19th century that were followed by their massive abandonment a few decades later (Parson 1999; McLauchlan 2006). The abandonment of marginal farmlands is a continuing trend (Smith et al. 2005; McLauchlan 2006), and the surface area of abandoned agricultural lands is probably underestimated (Vouligny and Gariépy 2008). The rehabilitation of fallow lands by silvicultural interventions that favor a natural succession or by plantation establishment can contribute to sequester large quantities of C (Harmon and Marks 2002; Anderson et al. 2006; Foote and Grogan 2010; Tremblay and Ouimet 2013). Natural regeneration has the advantage of being inexpensive and may contribute to preserving the genetic heritage and maintaining high diversity (Tremblay and Ouimet 2013). Naturally regenerated forests generally represent a greater stand density than a plantation (Peterken 1996). Natural regeneration reduces forest management costs (Tremblay and Ouimet 2013), but lowers the forester's control over the composition of regeneration. As a consequence, vulnerable tree species, such as balsam fir (Duveneck et al. 2014), can germinate and colonize perturbed sites and form stands that are not well adapted to climate change (Tremblay and Ouimet 2013). It is estimated that natural regeneration established on abandoned agricultural lands in Ontario can sequester 5% of the total annual CO_2 emissions of this province, which are estimated at 55 Tg of C (Foote and Grogan 2010).

The establishment of plantations represents a complement or an alternative to natural regeneration but remains an expensive option. The production of plants in a nursery, field preparation, reforestation, and work involved in plantation clearing represent additional costs compared to natural regeneration. However, plantations are generally more productive and sequester more C than naturally regenerated stands (Anderson et al. 2006; van Minnen et al. 2008; Coursolle et al. 2012; Tremblay and Ouimet 2013). If plantations of adapted species had been established at a rate of 73,000 ha year^{-1} in Ontario between 1990 and 2012, this would have allowed an additional sequestration of 1.6 million metric tons of total C when compared to natural regeneration (Colombo et al. 2005).

The assisted migration of certain forest species or genotypes is already applied in certain regions (Rehfeldt et al. 1999; Beaulieu and Rainville 2005; O'Neill et al. 2008a) and should increase considerably in magnitude in the future (Pedlar et al. 2012). This measure is considered as a necessity to ensure that forests retain optimal productivity and CO_2 sequestration capacity (Savva et al. 2007; O'Neill et al. 2008a; Pedlar et al 2012) under a climate regime that would have modified itself at a pace that neither gene flow nor natural migration could have compensated for.

Generally, if seedlings are planted outside of their usual climate zone, growth decreases and seedlings may be more vulnerable to spring frosts, climate extremes, and insect infestations (Beaulieu and Rainville 2005; O'Neill et al. 2008b). In anticipation of climate change, plantations will have to be established near their usual climate zone to allow species to acclimate to their new environment. In order to avoid stress that would be too severe, it would be better to reforest seedlings of southern provenance toward more northerly sectors (Rehfeldt and Jaquish 2010) using 1° of latitude as the maximum limit (Bernier and Houle 2005; Savva et al. 2007; McKenney et al. 2009) according to seed transfer techniques developed for a few species in a context of climate change (Beaulieu and Rainville 2005; Savva et al. 2007; O'Neill et al. 2008a,b).

There are three types of assisted migration: (1) the assisted expansion of populations, (2) the assisted expansion of the species' range, and (3) the introduction of exotic tree species.

1. The assisted expansion of populations is already applied when seedlings produced from the seeds of external sources are planted in regions where the genotype is believed to be better adapted to the climate that will prevail during the tree's life span. For several years now, statistical models have been used to determine the migration distance that should be respected in order to optimize plantation productivity (McKenney et al. 2009). For white spruce, one of the species most frequently planted in eastern Canada, it is estimated that the seed source transfer protocol used in the Province of Québec will still be valid for the next 50 years (Beaulieu and Rainville 2005). However, this information remains unknown for many species.
2. The assisted expansion of a species outside of its current range consists in introducing a species originating from a neighboring region into one where it has not yet migrated. Generally, the further away from the original seed source, the greater is the reduction in volume growth or survival rate (Beaulieu and Rainville 2005). Methods have been developed to assess, from climate projections, the ideal migration distance in order to obtain optimal growth for plantations in the future

(McKenney et al. 2009). In British Columbia, for example, the displacement distance of climate zones was estimated for the next 25 years to plan the establishment of plantations of species outside their current distribution areas (O'Neill et al. 2008a; Rehfeldt and Jaquish 2010). Although climate conditions are suboptimal at this time, they still allow seedlings to settle (McKenney et al. 2009), and a progressive enhancement of growth conditions during the tree's life span is expected (O'Neill et al. 2008a).

3. Finally, the introduction of nonnative species is the third type of assisted migration. Norway spruce (*Picea abies* [L.] Karst.), some species of larches (e.g., *Larix decidua* Mill., *Larix kaempferi* [Lamb.] Carrière), and hybrid poplars are examples of species that were introduced in several regions of eastern North America. Although this option is available to the practitioner, it remains a very controversial one (Aubin et al. 2011; Pedlar et al. 2012) and should be carefully monitored (Hunter 2007).

20.5 Forest Management Adapted to the Stand Level

In the eastern region of North America, at the temperate–boreal interface, there are no silvicultural measures specifically designed for the adaptation of stands to climate change (Patry et al. 2013). In the following section, we propose a sequence of silvicultural treatments that can contribute to mitigating the economic and ecological threats resulting from climate change. These silvicultural treatments are inspired by those that already exist here or elsewhere in the world, but have sometimes been adapted according to the implications of climate change. These silvicultural treatments may be applied to stands of different ages and composition and according to whether an even- or uneven-aged strategy is followed. For each silvicultural treatment, precisions are given on its application, advantages, and particularities in relation to climate change.

20.5.1 Educational Silvicultural Treatments

20.5.1.1 Stands in Regeneration

During the regeneration stage, the maintenance of site productivity and the restoration of forest biodiversity are the main silvicultural objectives for adaptation to climate change (Folke et al. 2004; Steffen et al. 2004; Fischlin et al. 2007; Schütz and Pommerening 2013; Puettmann and Tappeiner 2014). At this stage, in both even-aged and uneven-aged management regimes, reforestation and precommercial thinning will be used. The reforestation of poorly regenerated forest sectors (Williamson et al. 2009) and fallow lands (van Minnen et al. 2008; Tremblay and Ouimet 2013) with adapted species (Table 20.1) represents the main adaptation measures that can be used by the forester (Figure 20.1). A fallow land reforested with softwood species (2500 stems ha^{-1}) cumulates a total of ~ 30 tC ha^{-1} after 50 years compared to 21tC ha^{-1} for naturally regenerated fallow lands (Tremblay and Ouimet 2013). The forester must have a good knowledge of the ecological traits of the species used for reforestation or replacement planting. A species can be well adapted for a given region as long as its shade tolerance and optimal thermal zone are respected (Table 20.1). The range of temperatures is well known for most of the species used for reforestation, except for the white pine's minimum temperatures (Table 20.1). In this case, the range of temperatures is considered to be similar to the one observed for red pine.

TABLE 20.1

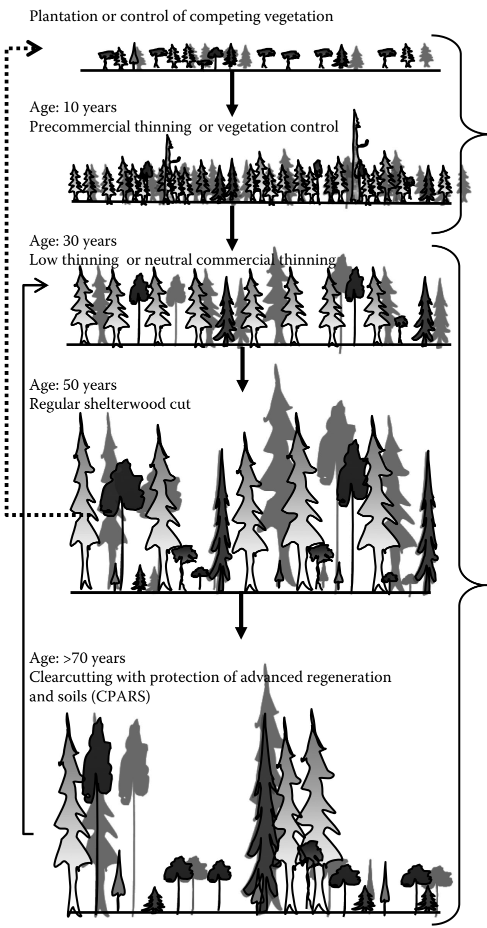
Temperature Range within the Distribution Area and Silvicultural Tolerances for Some Native Species of North America at the Seedling Stage

Scientific Name of Species	Average Temperature[18a,b] (Minimum and Maximum)	Shade Tolerance
Betula alleghaniensis	−18°C to 16°C[a]	Intermediate[3]
Acer saccharum	−18°C to 16°C[a]	Very tolerant[4]
Pinus strobus	−18°C to 21°C[a]	Intermediate[5]
Pinus resinosa	−18°C to 21°C[a]	Intolerant-intermediate[6]
Quercus rubra	4°C to 16°C[b]	Intermediate[7]
Quercus alba	−18°C to 21°C[a]	Intermediate to tolerant[8]
Carya ovata	4°C to 21°C[b]	Intermediate to tolerant[9]
Juglans nigra	7°C to 19°C[b]	Intolerant[10]
Juglans cinerea	4°C to 16°C[b]	Intolerant[11]
Prunus serotina	−8°C to 28°C[a]	Intolerant[12]
Fraxinus americana[1]	−14°C to 18°C[a]	Tolerant to intolerant[13]
Thuja occidentalis[2]	−12°C to 16°C[a]	Intermediate to tolerant[14]
Picea glauca	−29°C to 18°C[a,15a]	Intolerant-intermediate[15a–c]
Picea mariana	−20°C to 7°C[a]	Tolerant[16]
Picea rubens	−7°C to 14°C[a]	Tolerant[17]

1 White ash seedlings are very tolerant to shade and can survive with less than 5% of light.
2 At the seedling stage, the eastern white cedar (*Thuja occidentalis*) has a rather intermediate tolerance to shade.
3 Erdmann (1990); Kneeshaw and Prévost (2007); Raymond et al. (2006); Shields et al. (2007).
4 Godman et al. (1990).
5 Wendel and Smith (1990); Raymond et al. (2006); Burgess and Wetzel (2002) except for the minimum temperature.
6 Rudolf (1990).
7 Sander (1990).
8 Rogers (1990).
9 Graney (1990).
10 Williams (1990).
11 Rink (1990).
12 Marquis (1990).
13 Schlesinger (1990).
14 Johnston (1990).
15 (a) Nienstaedt and Zasada (1990); (b) Comeau et al. (2008); (c) Hébert et al. (2013).
16 Viereck and Johnston (1990).
17 Blum (1990).
18 (a) Represents the average temperature for the coldest month (minimum = January) at the northern limit and for the warmest month (maximum = July) at the southern limit of its current distribution. (b) Mean annual temperature minimum and maximum.

Precommercial thinning is the silvicultural treatment that allows the stand to maintain optimum productivity by managing the density and composition. This silvicultural treatment results in changing the structure of the stand (Schneider et al. 2013) and making more water available for residual trees, thus reducing mortality risks caused by prolonged droughts (Sohn et al. 2013). Stands located on rich soils should be primarily selected because of their capacity of reaction to thinning (Johnston 2009). Modulations in the application of precommercial thinning are possible and its resulting form depends on the composition of the stand. In the temperate–boreal transition zone, precommercial thinning prescriptions must aim at conserving all adapted tree species such as eastern

Even-Aged Regime



Educational Silvicultural Treatments

- Reforestation
- Control of competing vegetation
- Precommercial thinning (conifer or intolerant hardwood species)
- Precommercial thinning of tolerant hardwood (or by releasing elite trees)

Adaptation Measures to Climate Change

1-Reforestation of abandoned agricultural lands and poorly regenerated forested lands with adapted species according to bioclimatic zones
2-Preservation of the species that are tolerant to drought and/or insects
3-Establishment of plantations of adapted genotypes or species
4-Fragmentation and/or spreading through time of precommercial thinnings that simulate natural disturbances or reduce evapotranspiration on soils with low water retention application of precommercial thinning with variable density (e.g., 2000 to 5000 stems ha^{-1})
5-Prioritization of species well adapted to climate change at the expense of less well-adapted species during precommercial thinning
6-Preservation of long-lived adapted species of good quality (eastern white cedar, pines, maple sugar, oaks, *Fraxinus*)
7-Harvest of balsam fir or other species forming pure stands close to their southern limit of distribution
8-Preservation of fruit trees used by wildlife

Commercial Silvicultural Treatments

- Commercial thinning[1] (30 years)[2]
- Regular shelterwood cut (50 years) with undercover reforestation and/or in natural gaps with adapted species if regeneration of desired species is insufficient
- CPARS with variable retention (70 years +) or with the maintenance of clumps in association with replacement planting and/or plantation of adapted species if regeneration of desired species is insufficient after cut.
- Reforestation with adapted species

Note: The CPARS with the maintenance of clumps is not suggested if the balsam fir or other species vulnerable to climate change dominate the stand.

Adaptation Measures to Climate Change

1-Reduction of the rotation age if it is a stand composed of species vulnerable to climate change and in function of its latitudinal location
2-Exposition of the mineral soil by seed holes undercover to favor the establishment of regeneration
3-If the regeneration is insufficient, establishment of plantations of adapted genotypes or species
4-Favor species diversity
5-Reintroduction of adapted species if these have become rare
6-Variation in thinning modalities to retain diversity within the stand and leave more water available in the soil for residual stems
7-Optimization of the H/d ratio (<80 after treatment) to avoid windfalls

FIGURE 20.1
Sequence of silvicultural treatments adapted to climate change for the even-aged regime. [1]Can include thinning modalities by the bottom, by the top or neutral with the releasing of 150, 200, or 300 elite trees ha^{-1} with or without gaps or a combination of these modalities. [2]The age between parentheses is indicative and is function of the stand, its species composition, and site productivity.

white cedar, pines, spruces, and tolerant or semi-tolerant hardwoods along with other biodiversity components (fruit trees, noncommercial species, snags, etc.) (Figure 20.1). For stands composed of species sensitive to insects (Cappucino et al. 1998; Jactel and Brockerhoff 2007), diseases, or other factors such as overgrazing, the objective is to reduce their vulnerability. In certain regions, damages caused by specific faunal species can induce decreased productivity, especially by excessive grazing (Anderson et al. 2002; Danell et al. 2003; Frelich and Reich 2010; Fisichelli et al. 2012).

20.5.2 Commercial Silvicultural Treatments

Commercial silvicultural treatments recommended in the temperate–boreal transition zone of eastern Canada can be applied in several other regions that contain species that are particularly vulnerable to climate change, as is the case for the balsam fir (Ogden 2006; Williamson et al. 2009; Duveneck et al. 2014). Adaptation measures should consider its progressive replacement as soon as possible within the stand's life span, and this is also the case for all other species, such as white spruce (Fisichelli et al. 2013a; Duveneck et al. 2014), aspen, yellow birch, white birch, black spruce, and jack pine, judged as currently vulnerable or that will become so in the future (Duveneck et al. 2014). Subsequent silvicultural treatments will aim at maintaining or increasing stand productivity by the diversification of composition, structure, or both at the same time.

20.5.2.1 Adaptation Measures for Transitional and Mature Stands

20.5.2.1.1 Even-Aged Forest Regime (Single or Few Species)

Recommended silvicultural measures depend on the developmental stage of the stand from transitional to mature stages. When the competitive exclusion process is engaged after about 30 years or so of development, commercial thinning becomes one of the main silvicultural treatments that can be applied (Sohn et al. 2013; Magruder et al. 2013) (Figure 20.1). Commercial thinning offers several advantages, notably the delivery of forest products and the increase in C reserves (Harmon and Marks 2002). This intervention provides the possibility of harvesting species that are judged vulnerable while favoring the establishment of seedlings from long-lived species. Most long-lived species having small seeds, such as spruces (Ruel and Pineau 2002; Simard et al. 2003), pines (Cornett et al. 1998), eastern white cedar (Cornett et al. 2000, 2001; Larouche 2006), and yellow birch (Erdmann 1990; Shields et al. 2007), generally require specific germination conditions frequently associated with the presence of mineral soil (Cornett et al. 1998; Greene and Johnson 1998; Cornett et al. 2000) or rotten wood (Minore 1972; Greene and Johnson 1998; Cornett et al. 2000; Simard et al. 2003; Robert et al. 2012).

In subsequent developmental stages, contrasted silvicultural approaches between the south and north of the distribution area of species will have to be considered in order to account for the effects of climate change. For example, in a monospecific stand of balsam fir of 50 years or so located in the south of the species distribution area, stand recovery should be considered, particularly in the case of a spruce budworm outbreak or other insect pests (Williamson et al. 2009) (Figure 20.1, dotted arrow). When the balsam fir regenerates in abundance, a clearcut should be applied followed by field preparation and reforestation using adapted species. A balsam fir seedling that germinates now will develop under growth conditions that will become less favorable with time, particularly at the south of its distribution area (Johnston 2009; Chambers et al. 2013). However, in the northern sector of its distribution area, the treatment generally recommended will be a shelterwood cut followed by a regeneration protection cut 10 to 15 years later (Figure 20.1). When spruces, eastern white cedar, or other adapted species constitute an important component of the arborescent stratum, efforts should be devoted to the establishment of natural regeneration by exposing the mineral soil and maintaining a sufficient quantity of large woody debris on the soil (Simard et al. 2003). The progressive reduction of balsam fir proportion or of any other species judged vulnerable should be done for the benefit of adapted species.

20.5.2.1.2 Uneven-Aged Forest Regime

The structural conversion appears as an innovative adaptation approach, particularly in even-aged monospecific stands or those consisting of species vulnerable to climate change (Steenberg et al. 2011) (Box 20.2). Since this is a silvicultural approach that spans several decades (Schütz 1997, 2001; O'Hara 2001), the structural conversion provides the opportunity for managing at the same pace than the evolution of anticipated climate conditions. The type of intervention recommended to initiate structural conversion depends on the age of the stand.

In 30-year-old stands, it is suggested to apply a commercial thinning by releasing elite trees from competitors and create small gaps (Figure 20.2). In the context of silvicultural adaptation to climate change, an elite tree is a long-lived tree species, from the dominant or codominant class with a straight bole. The number of elite trees that should be released can be modulated in function of the stand's characteristics (initial stem density, quality of dominant and codominant stems, average diameter) and can vary from 50 to 400 stems ha^{-1} (Schütz 1997, 2001; Hanewinkel and Pretzsch 2000; Mason and Kerr 2004; Balleux and Ponette 2006; Davies et al. 2008; Susse et al. 2011; Sanchez et al. 2012; Sohn et al. 2013). The choice of elite trees must be made at the first thinning (Davies et al. 2008) without however completely releasing them. A certain number of elite trees can be released during the second thinning. Thinning should be conducted along with the exposition of the mineral soil in small patches and filling plantations with adapted species in natural or artificial gaps. An undercover filling plantation is possible in all types of stands provided that at least 25% of incident light reaches the forest floor at the time of plantation of shade-tolerant species (Greene et al. 2002). In order to promote plant growth undercover in young conifer stands, thinnings of light to moderate intensity must be frequent. Mixed stands dominated by hardwood species are more suitable for undercover plantation since they generally provide more light for seedlings during the growth period (Greene et al. 2002; Comeau et al. 2008).

The formation of small gaps emulates the effect of small windfalls to create heterogeneity in stands (Anderson 1951; Frelich and Lorimer 1991), whether these are conifer, mixed (Fahey and Puettmann 2007; Franklin et al. 2007; Hébert et al. 2013; Laarmann et al. 2013), or hardwood stands (O'Hara 2001), while allowing the natural or artificial regeneration to settle. In young stands, gaps should not exceed 0.05 ha, especially on rich sites, in order to halt the invasion of competing species and at the same time to allow the optimal growth of seedlings (Hébert et al. 2013). Gaps must be dispersed in such a way as to constitute 9%–30% of the stand's surface area (Kneeshaw and Prévost 2007). For each silvicultural intervention, the existing gaps must be enlarged by the harvest of several peripheral trees to allow seedlings to receive at least 10% of incident light for tolerant hardwood (Anderson 1951; Kerr et al. 2010) and 25% for tolerant conifer species (Greene et al. 2002).

Ten years later, a second commercial thinning by the release of elite trees can be performed. However, the number of elite trees to be released during the second intervention will be inversely proportional to the number of elite trees released in the first thinning

BOX 20.2 STRUCTURAL CONVERSION

Structural conversion is a silvicultural treatment that requires a long period (Reininger 1987; Schütz 1997, 2001; Hanewinkel and Pretzsch 2000; O'Hara 2001). This silvicultural approach consists of transforming an even-aged stand into an uneven-aged, irregular stand without using clearcutting, except for creating small gaps (Figure 20.2). There are four steps to be followed (O'Hara 2001; Schütz 2001). No step should be omitted at the risk of jeopardizing the success of subsequent steps. The first step is to ensure that the stand is differentiated. The main differentiation factors can be represented by competition indices between stems such as the tree surface area, the dominant height/diameter ratio and the Hart-Becking coefficient. A stand basal area higher than 25 m^2 ha^{-1} indicates that the competition has begun. However, this threshold may vary depending on the species and site productivity. The height/diameter ratio of dominant trees for the main conifer species should be maintained below 80 (Becquey 1986). The targeted value of the Hart-Becking coefficient at the time of the first thinning varies in function of the stand's age and species composition (Pardé 1961). For coniferous species such as eastern North American spruces, this coefficient must be between 15 and 20 (Pardé 1961; Riou-Nivert 1984; Prégent 1998). Beyond a value of 20, the stand does not have a density problem, but when below 15, the stand is potentially vulnerable to wind. For pines, the value of the Hart-Becking coefficient at the first thinning is around 22 (Riou-Nivert 1984). The second step consists in first establishing, as early as possible in the life of the stand, a regeneration of long-lived species in quantity and quality and then to create a heterogeneous horizontal structure. It's the abundance of regeneration (Schütz 1997; Hanewinkel and Pretzsch 2000; Schütz 2001) of long-lived species (Schütz 2001) that enables the initiation of the conversion process. For the regeneration to establish, interventions must be frequent to allow seedlings to receive sufficient light (Schütz 1997; 2001; Davies et al. 2008; Susse et al. 2011). The third step is to make sure that the regeneration is well established and that it will gradually form at first a bi-storied stand, and then an uneven, irregular stand. If this sequence is respected, the conversion process is under way. The fourth step is to practice uneven-aged management interventions in order to preserve the irregular structure of the stand. The absence of long-lived species in the original stand can be compensated by replacement planting in gaps or undercover if understory light conditions are favorable. Species such as pines, white spruce, eastern white-cedar, red spruce, yellow birch, sugar maple, and oaks can be used for replacement planting based on the regions and their ecological requirements.

GAPS

Gaps have been used for a long time in silviculture of tolerant hardwood (O'Hara 2001) and coniferous (Anderson 1951; Franklin et al. 2007) stands. They have several silvicultural and ecological roles notably to allow natural or artificial seedlings to receive more light and to emulate natural disturbances (O'Hara 2001; Franklin et al. 2007). This is the reason why we associate gaps to structural conversion since it helps in orienting stands toward an irregular structure from the first thinning and also in subsequent silvicultural interventions. In natural conditions, their surface area can vary from a few tens to 500–1000 m2. These gaps are aimed at emulating small disturbances such as windfall or mortality by small groups of trees. The size of the gap influences local environmental conditions (Canham and Marks 1985; Bradshaw 1992; Fahey and Puettmann 2007), hence the importance of knowing the requirements of each species.

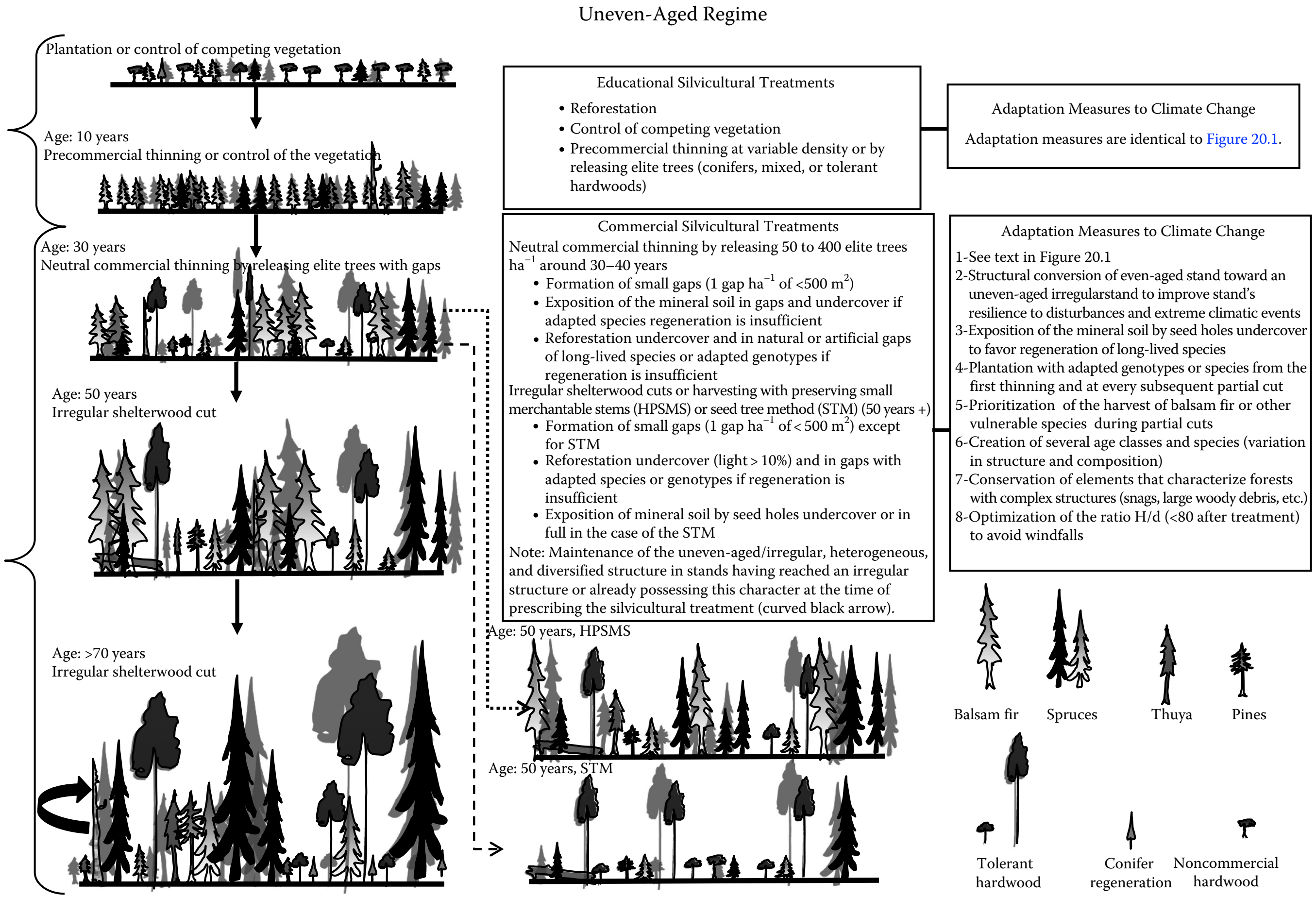


FIGURE 20.2
Sequence of silvicultural treatments adapted to climate change for the uneven-aged regime. [3]The modalities of commercial thinning can be applied under the condition that the stand basal area is ≥28 m² ha⁻¹. Commercial thinning can be applied twice before moving to an irregular shelterwood cut regime.

(Hanewinkel and Pretzsch 2000; Mason and Kerr 2004; Balleux and Ponette 2006). The number of elite trees can also be constant through time, whereas the number of competitive trees harvested can change (Susse et al. 2011; Sohn et al. 2013).

In 50-year-old stands, two situations are possible: (1) if the stand contains at least 50% of long-lived species (spruces, eastern white cedar, oaks, yellow birch, pines, sugar maple, hickories, ashes), the irregular shelterwood cut system should be applied (Figure 20.2). The irregular shelterwood cut allows a progressive establishment of regeneration and creates an irregular structure with time (Grassi et al. 2003). The harvest of 30%–40% of the stand basal area at intervals of 15–25 years and moderate interventions provide for a steady flow of light under the forest cover necessary for the establishment of regeneration (Grassi et al. 2003). The creation of gaps of 200–500 m^2 and infilling plantations are also suitable silvicultural tools to promote the establishment of regeneration; (2) When the stand consists mostly of balsam fir (or of another vulnerable species), while long-lived species occupy more than 30% of stand basal area, the harvesting with protection of small merchantable stems (Figure 20.2, dotted arrow) is recommended. For stands dominated by long-lived hardwood species, the seed tree method (STM) is proposed (Figure 20.2, broken arrow). The STM should be applied only when long-lived species dominate the stand (Figure 20.2).

In stands that are 70 years old or older with a long-lived species component greater than 50% (Figure 20.2), the regime of irregular shelterwood cuts at intervals of 15–25 years is the most appropriate silvicultural approach in order to maintain structure and control composition (Figure 20.2, curved arrow). In this type of stand, the structure is already uneven aged or irregular and gaps are already present. If more gaps are required at the time of the application of the treatment, they must not exceed a size of 0.2 ha (Kneeshaw and Prévost 2007; Kneeshaw et al. 2008) to avoid the invasion of competing species.

The challenge for today's forest specialists is to implement adaptive measures in an emergency context that will have positive impacts much later on (Brooks et al. 1998; Lindner et al. 2000; Chapin et al. 2004; Goldblum and Rigg 2005; van Minnen et al. 2008; Williamson et al. 2009). Current silvicultural practices must be improved (Johnston 2009; Magruder et al. 2013; Patry et al. 2013; Wang et al. 2013) to allow the maintenance of site productivity at an optimal level in a context of climate change. Silvicultural treatments applied in the last decades were primarily established for economic reasons. Although being still relevant today, this trend is being reconsidered for environmental reasons. Climate change is largely responsible for this shift in favor of a forest management approach aimed at improving the adaptability of forest ecosystems to changing environmental conditions.

The costs to improve the adaptability of forests toward climate changes will be very high if we do not start as of now to modify our silvicultural practices (Maclean et al. 2010). Large-scale implementation of the mitigative measures proposed in this chapter can generate important social, economical, and ecological benefits, and this is at a lesser cost. Recent studies have shown that a managing strategy focused on diversity could lead to greater resilience in forest ecosystems and generate a greater and more regular income compared to a management strategy that is solely based on woody matter production (Davis 2010; Anonyme 2013; Dymond et al. 2014). Managing strategies can differ from one region to another and will depend on the state of forests or on their vulnerability to disturbances (Anonyme 2013). Adapted practices that will be integrated in management plans will significantly reduce the vulnerability of forests to epidemics or to other types of disturbances after a few decades only (Spittlehouse 2005; Bunnell and Kremsater 2012).

Forests provide many products and services such as timber, wildlife habitat, and environmental services, which are values that are essential to a collective well-being. Forest economy and governmental policies should, as of now, consider all of these values when calculating income, particularly in the context of global changes such as those that will be imposed by climate changes (Dymond et al. 2014). The complete life cycle of wood, from its production to its processing, use, and eventual decomposition, should be modeled to estimate more precisely its role in sequestering C from the atmosphere and in mitigating greenhouse effect. Studies will be needed in order to analyze in greater detail the long-term costs and benefits of the mitigation measures that are proposed in this chapter.

20.6 Conclusion

Vast regions bordering the temperate northern forest and the southern part of the boreal forest might strongly react to ongoing climate change because this part of the globe is experiencing a rapid increase in temperature (Plummer et al. 2006; Christensen et al. 2007; Lemmen et al. 2008; Fischlin et al. 2009; Lucier et al. 2009). In this chapter, we presented proactive measures to improve forest adaptability to climate change that included several of the practices associated with both ecosystem and forest management aimed at structural diversity. Concurrent to these, reactive management measures that respond to ecological disturbances could also increase the adaptability of forests to climate change (Kuparinen et al. 2010). Several of these practices are already applied locally in North America. However, elements that specifically aim at adapting to climate change as it is proposed in this chapter must still be integrated in management guides (Patry et al. 2013). Most silvicultural guides in North America do not consider climate change in their planning strategies. Climate change yet offers an exceptional scientific challenge to develop an adapted silviculture. Adapted management contributes to maintaining very high productivity of forests increasing the capacity of forests to sequester C and maintaining sustainable socioeconomic values (Maclean et al. 2010). Considering the unprecedented pace at which climate change is taking place, there is an urgent need for immediate modifications of our forest management practices (Smit et al. 1996; Smit et al. 2000; Lazar 2005; McKinnon and Webber 2005; Lemprière et al. 2008).

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