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Does partial harvesting promote old-growth attributes of boreal mixedwood trembling aspen (*Populus tremuloides* Michx.) stands?

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ABSTRACT

In the current context of forest ecosystem management, partial harvesting has been proposed as a silvicultural tool to augment forest variability on managed landscapes and to accelerate the development of structural and compositional attributes of old-growth/late successional stands. The aims of this paper were to (1) identify and characterize, based on the literature, the structural attributes of old-growth aspen-dominated stands in the North American boreal mixedwood forest, and (2) examine the short-term potential of partial harvesting in aspen-dominated stands to accelerate stand development toward these old-growth characteristics. Two stand types – pure aspen (93% aspen basal area) and mixed aspen (81% aspen basal area) – were monitored over a 12-year post-treatment period. The scientific literature suggests that compared to pure, even-aged premature or mature stands, old-growth aspen stands have lower merchantable stem densities and basal area, more large aspen stems, higher stem size variability, more than one cohort of trees, greater percentage area occupied by gaps, higher expanded gap area, and more and larger snags and downed wood. In addition, old-growth aspen mixedwoods characteristically have more shade-tolerant conifers in understory and overstory layers than younger, mature stands. Results of this study indicate that light thinning from below (33% basal area removal) applied in pure aspen stands successfully retained most of the structural attributes of mature aspen stands, but did not generally "accelerate succession" toward old-growth traits in the 12-year time interval since treatment. A dispersed free thinning (45% basal area removal in all merchantable size classes) applied in mixed aspen stands showed its potential to "accelerate succession" by creating canopy gaps similar to old-growth aspen stands and by promoting recruitment of both tolerant and intolerant tree species. Two high intensity partial harvesting treatments, a thinning from above of 61% basal area in pure aspen stands and 400 m^2 gap cuts (54% basal area removal) in mixed aspen stands may set back stand development by disproportionally favoring recruitment and growth of intolerant hardwood species.

1. Introduction

The concept of forest ecosystem management (FEM) has taken hold in many parts of the World (Gustafsson et al., 2012; Lindenmayer et al., 2012), including Canada (Burton et al., 2003; Gauthier et al., 2009). Forest ecosystem management recognizes the importance of mitigating the differences between natural (that is, unmanaged and of natural disturbance-origin) and managed forest landscapes, and as such, silvicultural practices are underpinned by an understanding of how natural disturbance and ecosystem processes affect stand dynamics (Grumbine, 1994; Christensen et al., 1996). The natural disturbance emulation approach of FEM aims, in part, to mitigate the undesirable impacts of generalized application of clear-cutting and its variants on biodiversity (Fedrowitz et al., 2014) and ecosystem processes (Likens et al., 1978; Keenan and Kimmins, 1993), thus favoring long-term sustainability of ecosystem goods and services (Christensen et al., 1996).

Partial harvesting has been identified as a key silvicultural tool in the implementation of FEM in the boreal forest (Lieffers et al., 1996; Bose et al., 2014c). Partial harvesting is a generic term, which refers to a whole range of harvesting treatments from clear-cutting with dispersed retention in which a few merchantable stems are left on site, to single-tree selection systems. It is assumed that partial harvesting can (1) contribute to maintaining ecosystem functions within their historical range of variability by retaining greater residual structure in harvested forests (Drever et al.,

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2006; Franklin et al., 2007; Gauthier et al., 2009), and (2) potentially accelerate stand development toward an old-growth stage – or accelerate the acquisition of compositional and structural characteristics associated with the old-growth stage. This may occur, in part, by creating growing space of variable sizes for new cohorts of trees (Franklin et al., 2002; Harvey et al., 2002). Old-growth stands have been recognized as functionally and structurally diverse relative to young, intensively managed stands (Spies and Franklin, 1988; Mosseler et al., 2003; Franklin and Van Pelt, 2004) and stands with high structural variability are considered more likely to provide a variety of wildlife habitats (Fischer et al., 2006) and, at least theoretically, to increase ecosystem resilience to environmental stresses (Drever et al., 2006).

In Canada, boreal mixedwoods generally occur on relatively productive sites and have long been recognized as being among the most structurally complex stand types in the Canadian boreal forest (De Grandpré and Bergeron, 1997; Chen and Popadiouk, 2002; Haeussler et al., 2007). In boreal mixedwoods, shade-intolerant hardwoods, mostly trembling aspen (*Populus tremuloides* Michx.) and white birch (*Betula papyrifera* Marsh), and shade-tolerant conifers coexist in different proportions depending on time since the last stand replacing fire, climatic factors and interactions between a range of abiotic and biotic factors (Bergeron et al., 2014; Nlungu-Kweta et al., 2014). Locally, trembling aspen can regenerate profusely by suckering (vegetative reproduction from roots), a process which is generally favored by severe disturbances (Perala, 1974; Frey et al., 2003; Brais et al., 2004), and boreal aspen stands have been traditionally managed under even-aged (clear-cut) silvicultural systems (MacDonald, 1995; Bergeron et al., 2002). However, studies conducted in boreal mixedwood forests have shown that, in the absence of fire, aspen may regenerate successfully in gaps, leading to older, uneven-aged stands with distinct aspen cohorts (Bergeron, 2000; Cumming et al., 2000; LeBlanc, 2014).

Regional studies have provided insights into the range of attributes that define old-growth aspen stands or mixed aspen stands in the boreal forest (Lee et al., 1997; Bergeron, 2000; LeBlanc, 2014). However, a more comprehensive review of the attributes of old-growth boreal trembling aspen stands is required to assess the effectiveness of partial harvesting of even-aged aspen stands to promote the development of these attributes. The potential of partial harvesting to promote old-growth characteristics has been tested for northern hardwood forests in the United States (Singer and Lorimer, 1997; Goodburn and Lorimer, 1998; Keeton, 2006), and Canada (Angers et al., 2005), and in other parts of the world (Barbati et al., 2012; Motta et al., 2014), but not for aspen-dominated boreal mixedwoods of North America. Studies conducted in boreal mixedwoods have shown that partial harvesting can create multi-layer canopies by favoring recruitment of intolerant hardwood regeneration and establishment of conifer regeneration (Prévost and Pothier, 2003; Man et al., 2008a; Bose et al., 2014b). However, Haeussler et al. (2007) found that while partial harvesting treatments in aspen-dominated mixedwoods may retain attributes of un-harvested stands, in the short term, they do not necessarily hasten the development of older stand attributes. Moreover, by destroying well-decomposed logs (Brais et al., 2004), partial harvesting can also cause a loss of structural variability and species diversity (Haeussler et al., 2007).

The objectives of this study are to (i) identify and quantify structural attributes that characterize old-growth aspen-dominated mixedwoods of the North American boreal forest and (ii) examine whether specific partial harvesting treatments applied 12 years previously in pure and mixed aspen stands promote structural attributes of old-growth stands in the mid-term. Using percentage of basal area removal as a proxy for harvesting intensity, we tested the following hypotheses: (1) low intensity, diffuse partial harvesting creates few large gaps and retains most of the structural attributes of even-aged stands (O'Hara, 1998; Haeussler et al., 2007); (2) high-intensity partial harvesting treatments applied in either a regular (diffuse) or a gap pattern create a higher percentage of canopy gaps and wide tree spacing. This in turn will produce greater variability in tree size classes through recruitment and growth of a second cohort of aspen (Ball and Walker, 1997; McCarthy, 2001; O'Hara, 2001) and promote the growth of saplings of late successional species, when present (Brais et al., 2013; Prévost and DeBlois, 2014). However, high-intensity partial harvesting will reduce the density of large trees, the density and basal area of standing snags and the volume of downed logs relative to untreated control stands (Angers et al., 2005; Keeton, 2006).

2. Methods

The first objective was addressed through a search of the scientific literature conducted in July–August 2014 to collect studies reporting on structural attributes of old-growth aspen-dominated boreal mixedwoods of North America. Pertinent scientific publications were identified using online search engines Google Scholar and Web of Science and combinations of the following keywords: "boreal", "aspen forest", "aspen stand", "aspen mixedwoods", "old-growth", "forest succession", "coarse woody debris", "snags", "gaps". We retained publications that met the following criteria: (1) sites were located within the boreal biome of North America, (2) stands reported on originated from wild fire and were naturally regenerated with trembling aspen as the dominant early successional species, (3) age of stands or time since stand-replacing fire were known. Among these publications, we further selected for those that (1) compared structural attributes between young-mature aspen, old-growth aspen and late-successional forests, or (2) presented data on stand structural attributes such as canopy, understory vegetation, gaps or deadwood (snags and downed logs) or (3) described changes in these attributes through natural succession. If a number of publications reported data from common sites, only the most informative publication was retained. We finally retained 19 studies conducted in the Canadian provinces of Alberta (e.g., Lee et al., 1997, 2000), Saskatchewan (e.g., Hobson and Bayne, 2000), Manitoba (e.g., Ball and Walker, 1997; LeBlanc, 2014), Ontario (e.g., Basham, 1958; Hill et al., 2005) and Québec (e.g., Kneeshaw and Bergeron, 1998; Bergeron, 2000) as well as in Minnesota, USA (e.g., Frelich and Reich, 1995) (Table 1). Most studies were published in peer-reviewed journals and provided qualitative or quantitative information on structural attributes of old-growth aspen forests.

For our purposes, old-growth was defined as stands between 100 and 200 years of age (LeBlanc, 2014), corresponding to the period following the onset of mortality of the initial post-fire aspen cohort and during which understory stems are recruited into the canopy (Kneeshaw and Gauthier, 2003). The upper limit (200 years) corresponds conceptually to the moment when aspen stems no longer constitute a major portion of stand basal area (Bergeron, 2000). This stage associated with old-growth aspen stands has also been described as an intermediary successional stage in boreal mixedwoods (Bergeron and Harper, 2009).

2.1. Study sites

The second objective was addressed using empirical data. This empirical part was conducted in the Lake Duparquet Research and Teaching Forest (LDRTF) in the Abitibi region of northwestern Quebec, 45 km northwest of the city of Rouyn-Noranda (48°26′N–48°32′N, 79°16′W–79°29′W). The region is characterized by the

Table 1
Structural attributes of old-growth trembling aspen stands in North American boreal mixedwood forests. Attribute values are based on a literature review (see methods). Certain references did not provide quantitative values for old-growth attributes. Attributes not measured in the current study mentioned as such.

Stand structural characteristics	Attributes of old-growth aspen stands relative to younger, homogenous stands	Ref.	Attributes measured in current study
Stand age	100–200 years	19	Not used in this study
Horizontal structure	Lower total merchantable stem density due to mortality (≈640–900 stems ha^{-1})	4,6,7	Stem density (⩾10 cm DBH, stems ha^{-1})
	Lower merchantable stem density of intolerant hardwoods due to the mortality of first cohort aspen, (≈215–650 stems ha^{-1})	10,15	Intolerant hardwood density (⩾10 cm DBH, stems ha^{-1})
	Higher stem density of shade-tolerant conifers due to the recruitment in canopy gaps (≈200–375 stems ha^{-1})	10,18	Shade-tolerant conifer stem density (⩾10 cm DBH, stems ha^{-1})
	Lower stand basal area due to partial mortality of first cohort aspen (≈25–28 m^2 ha^{-1})	10	Stand basal area (⩾10 cm DBH, m^2 ha^{-1})
	Wider range of diameter size classes (high standard deviation of DBH)	19	Standard deviation of DBH
	Higher mean stand DBH (≈29–45 cm) due to presence of large, old aspen and spruce stems, or lower following dieback of large aspen trees	6,7,10	Quadratic mean DBH (cm)
	Wider range of tree spacing and higher horizontal structural variability	14	Not measured
Canopy gaps	Higher percentage of canopy gaps (≈19–35%) and expanded canopy gaps, (≈26–32%) of total stand area	9,15	Percentage of canopy gaps (%)
	Higher variability in canopy gap area (≈6–1200 m^2) and expanded canopy gap area (≈34–1450 m^2)	9,15	Expanded canopy gap area (m^2)
Vertical structure	Greater presence of large, old canopy trees (⩾15% of total stand density or ≈96–115 stems ha^{-1})	11,12,13	Density of large trees (⩾30 cm DBH, stems ha^{-1})
	Multi-layered tree canopy	3,4,19	Not measured
	Wider range of height size classes (high standard deviation of tree height)	19	Standard deviation of tree height
	Higher maximum tree height (≈22–30.0 m)	6,7,16	Maximum height (m)
	Higher ratio of sub-canopy to canopy basal area (range 0.8–2.0)	12	Ratio of sub-canopy to canopy basal area
Understory structure	Higher density of shade-tolerant conifer regeneration (balsam fir, white and black spruce, eastern white cedar)	3,5,9,10,18	Shade-tolerant conifer sapling density (2–9.9 cm DBH, stems ha^{-1})
	Lower density of intolerant hardwood regeneration in small gaps and presence of shade-tolerant conifers. Large gaps and low conifer presence corresponds to higher densities of intolerant hardwood regeneration	2,3,5	Intolerant hardwoods sapling density (2–9.9 cm DBH, stems ha^{-1})
	Higher species and structural diversity of non-tree species including shrubs, herbs and other vascular and non-vascular plants	7,17	Density of woody shrubs (2–9.9 cm DBH, stems ha^{-1})
Deadwood structure	Higher density and basal area of snags, excluding snags and logs of pre-fire origin. (snag density ≈ 338–675 stems ha^{-1} with large snag (⩾20 cm DBH) density representing 15–20 % of total)	4,6,8,1018	Density of snags (⩾10 cm DBH stems ha^{-1}) Basal area of snags (⩾10 cm DBH m^2 ha^{-1})
	Higher volume of downed logs (117–132 m^3 ha^{-1}) and more large logs (excluding pre-fire logs)	4,6,7	Volume of downed logs (m^3 ha^{-1})
	Greater range of decay classes present and higher percentage of well-decayed downed wood	1,2	Not measured

1 – Basham (1958), 2 – Thomas et al. (1960), 3 – Frelich and Reich (1995), 4 – Schieck et al. (1995), 5 – Ball and Walker (1997), 6 – Lee et al. (1997), 7 – Crites and Dale (1998), 8 – Lee (1998), 9 – Kneeshaw and Bergeron (1998), 10 – Bergeron (2000), 11 – Hobson and Bayne (2000), 12 – Lee et al. (2000), 13 – Schieck et al. (2000), 14 – Kneeshaw and Gauthier (2003), 15 – Hill et al. (2005), 16 – Savignac and Machtans (2006), 17 – Haeussler et al. (2007), 18 – Thompson et al. (2013), 19 – Leblanc (2014).

presence of extensive clay deposits left by proglacial Lake Ojibway (Vincent and Hardy, 1977) and rich clay soils on upland sites (Canada Soil Survey Committee, 1987). The climate is continental with a mean annual temperature of 0.7 °C and mean annual precipitation of 890 mm (Environment Canada, 2011).

The LDRTF is located in the balsam fir-white birch bioclimatic domain (Saucier et al., 1998). Forests of the region are characterized by a mixed composition of boreal conifers, and shade-intolerant broadleaved species. Trembling aspen, white birch (*Betula papyrifera* Marsh), and jack pine (*Pinus banksiana* Lamb.) are the most frequent early successional species. Balsam fir (*Abies balsamea* (L.) Mill.) is the dominant species in late-successional forests on mesic sites, and is associated with white spruce (*Picea glauca* [Moench] Voss), black spruce (*Picea mariana* [Mill.] B.S.P.) and eastern white cedar (*Thuja occidentalis* L.) (Bergeron, 2000).

The SAFE Project (*Sylviculture et aménagement forestier écosystémiques*) (Brais et al., 2004, 2013) is a series of replicated experiments set in the LDRTF. Experiments were designed to validate the ecological and operational feasibility of a FEM approach involving partial harvesting in the eastern Canadian boreal mixedwoods (Bergeron and Harvey, 1997; Bergeron et al., 2002). The study makes use of data from two experiments of the SAFE project. The first one was set in "pure aspen stands" which originated from a wildfire in 1923. Average pre-treatment stand basal area was 42.1 m^2 ha^{-1} of which 92.6% was trembling aspen and 3.3% conifer species. In the winter of 1998–1999, three harvesting treatments, including a no harvest control and two intensities of partial harvesting were applied according to a complete randomized block design with three replications (blocks) of each treatment. Each block contained the three harvesting treatments, each applied to an experimental unit (EU). The sizes of EUs ranged from 1.4 to 9.9 ha (mean = 3.7 ha). The largest and smallest EUs were both control stands and surrounded by undisturbed forest. Harvesting treatments were applied using manual felling and bucking and logs were forwarded using small skidders. All trees were removed from trails that were, on average, 4.5 m wide and spaced at 30 m (Brais et al., 2004). The two partial harvesting treatments were designed to remove 33% (1/3 partial cut) and 61% (2/3 partial cut) of merchantable basal area (primarily aspen) in an evenly dispersed spatial pattern. Stands in the 1/3 partial cut were low thinned while stands in the 2/3 partial cut were primarily crown thinned; these treatments aimed to emulate the natural dynamics of self-thinning and stand senescence, respectively (Brais et al., 2004). In silvicultural terms, these treatments could be referred to as light, low thinning and heavy, crown thinning, respectively, but for consistency with previous publications, we maintain the 1/3 and 2/3 partial cut terminology throughout this paper.

"Mixed aspen stands" in the SAFE project originated from a wildfire fire in 1910. Average pre-treatment stand basal area was 41.0 m^2 ha^{-1} of which 80.8% was trembling aspen and 17.8% conifer species. In the winter of 2000–2001, three harvesting treatments, again including a no harvest control and two partial harvesting treatments, were applied. Similar to the design in the pure aspen stands, treatments in the mixed aspen stands were applied according to a complete randomized block design with three replications (blocks) of each treatment. Each block contained the three harvesting treatments, each applied to an EU. Experimental units ranged from 1.1 to 3.4 (mean size = 2.2 ha) with only two EU smaller than 1.5 ha. All harvesting treatments were applied using multifunctional (short-wood) harvesters and forwarders. The two partial harvesting treatments were (1) an evenly dispersed treatment that removed 45% of BA aimed to emulate individual-level tree mortality and (2) 400 m^2 gap cuts (average 54% BA removal) aimed to emulate tree mortality in patches. In dispersed cuts, all trees were removed in 5–6 m wide hauling trails and approximately 25% of stems were harvested to a depth of 6–7 m in the adjacent strips. In gap cuts, gaps were created by alternately harvesting stems in the trail only and enlarging the cutting area to a width of 6–7 m on either side of trails (total width 18–21 m) along a 20 m length creating gaps of approximately 360–420 m^2. In both treatments, an unharvested band of 5–6 m was left between each sequence of trail – partially harvested strip. In silvicultural terms, these two treatments could be considered an intermediate-intensity free thinning (cutting in all commercial stem sizes) and group shelterwood treatments, respectively, but again, for reasons of consistency, we refer to them as the 45% dispersed cut and gap cut treatments.

Besides differences in overstory composition, the main difference between the two stand types was in the seedling and sapling layers: balsam fir was very dense in mixed aspen stands, whereas total conifer regeneration was very low and a woody shrub, mountain maple (*Acer spicatum* Lamb.) dominated the regeneration layer in pure aspen stands.

2.2. Field methods

In each EU, five permanent sample plots (PSP, 400 m^2, radius = 11.28 m) were established before treatment application. All stems (trees and shrubs) greater than 5 cm at breast height (1.3 m) were identified to species, tagged, and their diameter at breast height (DBH) was measured. In the northeast quadrant (100 m^2) of each PSP, all stems between 2.0 and 4.99 cm DBH were also identified to species, tagged, and their DBH measured. A similar inventory was conducted for snags (dead stems > 1.3 m in height) within PSP. Snags were identified to species, measured (DBH), and tagged. Immediately following harvesting, a tally of all residual stems was compiled. All PSP in the pure aspen and mixed aspen stands were measured again 12 years after treatment application.

Twelve years after treatment application, canopy gaps were measured in all experimental units using transects oriented perpendicular to skid/forwarding trails (250 m total in each EU). Despite the small size of some of the experimental units of the two studies, we believe the measurement protocols, including the 250 m transects and 400 m^2 PSPs, encompassed the within-stand variability and patterns of the measured attributes. Canopy openness was assessed by observing vertically every 30 cm along transects and noting the vertical space as either covered with tree crown or open due to the partial harvesting or tree mortality. Canopy gap was defined as "the vertical projection of a canopy opening (the area with no overhead foliage). Measurements in transects allowed the following calculations: (i) gap length (m): distance between two crown edges on transect; (ii) expanded gap area (m^2): the area circumscribed by the stems of trees whose crowns define the canopy gap; and (iii) percentage of canopy gaps (%): total gap length on a transect × 100/total length of the transect. The formula of an ellipse was used to calculate the expanded canopy gap area (see details in Runkle, 1982; Kneeshaw and Bergeron, 1998). In all experimental units, the volume of downed logs was inventoried twelve years after treatment application using the line intercept method by Van Wagner (1982). Along each of the equilateral triangle (length = 30 m), the frequency of downed logs was recorded by diameter size classes (5 cm: 2.5–7.6 cm; 10 cm: 7.6–12.5 cm; 15 cm: 12.6–17.5 cm; and 17 + cm: 17.6 cm and greater). Downed log volume was calculated using the following formula of Van Wagner (1982).

$$V = \left(\frac{1.234}{L}\right) \times N \times (Diameter \times Diameter)$$

where V is the volume of logs, L is the total length of the triangle, N is the number of logs and *Diameter* is the log diameter.

2.3. Data analysis

Based on our dataset, we measured 18 structural attributes describing old-growth characteristics of aspen-dominated boreal mixedwoods (Tables 1 and 2). Tree species were divided in two classes in relation to their successional status. Intolerant hardwoods consisted of trembling aspen, balsam poplar (*Populus balsamifera* Gray) and white birch, whereas the shade-tolerant conifers included white spruce, black spruce, balsam fir and eastern white cedar. Ratio of sub-canopy to canopy basal area was calculated following Lee et al. (2000), where dominants and co-dominants (⩾20 cm DBH) represent canopy trees and intermediate and suppressed (5–19.9 cm DBH) represent sub-canopy trees. Tree height was calculated individually for each stem using species-specific allometric equations of Beaudet et al. (2011) These authors provided parameter values with 95% confidence intervals; R^2 values (mean corrected) for all species except jack pine ranged from 0.68 to 0.93 (The R^2 value of jack pine was 0.35 but we have very few jack pine stems in the study). These equations were developed using a dataset from our study sites and has been used in other publications (e.g., Bose et al., 2015). Maximum height is the height of the tallest tree in a PSP. Standard deviations of DBH and height were used to indicate horizontal and vertical structural variability, respectively (Zenner, 2000). Because gap measurements were not made prior to treatment applications, we used stand density and basal area of live and dead trees as indicators of canopy closure to test pre-treatment differences between treatments.

2.4. Statistical analysis

Effects of harvesting treatments on structural attributes immediately and 12 years after harvesting were assessed by linear mixed models (Pinheiro and Bates, 2000) using the nlme package in R (Pinheiro et al., 2011; R-Development-Core-Team, 2011). Blocks and experimental units (EU, $n = 9$) nested within blocks were treated as random factors. Treatment was treated as a fixed factor. Stands and time periods (immediately after and 12 years after treatment) were analyzed separately and the differences among treatments were tested by means of contrasts, (1) controls

Table 2
Effects of partial harvesting on stand structural attributes at year of treatment application and 12 years later. Significance of fixed effects is based on contrasts between pairs of categorical variables (treatments). Note: Number of experimental units, $n = 9$; 1/3 PC: 33% BA removal primarily of suppressed and intermediate stems in pure aspen stands; 2/3 PC: 61% BA removal primarily of dominant and co-dominant stems in pure aspen stands; DC: 45% BA removal using free thin in dispersed pattern in mixed aspen stands; GC: 54 % basal area removal in a gap pattern (400 m^2 gaps) in mixed aspen stands; PA: pure aspen; MA: mixed aspen; NS: $p \geqslant 0.051$, not included in analysis.

Response variables	Year of treatment application				12 years after treatment application			
	PA, Control Vs 1/3 PC	PA, Control Vs 2/3 PC	MA, Control Vs DC	MA, Control Vs GC	PA, Control Vs 1/3 PC	PA, Control Vs 2/3 PC	MA, Control Vs DC	MA, Control Vs GC
Horizontal structure								
Stand density (⩾10 cm DBH)	0.037	0.009	NS	NS	NS	0.012	0.007	0.002
Intolerant hardwood tree density (⩾10 cm DBH)	0.018	0.005	NS	0.025	NS	0.005	0.018	0.006
Shade-tolerant conifer tree density (⩾10 cm DBH)	NS	NS	NS	NS	NS	NS	NS	NS
Stand basal area (⩾10 cm DBH)	0.003	0.000	0.006	0.002	0.019	0.000	0.002	0.000
Mean DBH (⩾10 cm DBH)	NS	NS	NS	NS	NS	NS	NS	NS
Standard deviation of DBH (⩾10 cm DBH)	NS	NS	NS	0.039	NS	NS	NS	NS
Canopy gap structure								
Percentage of canopy gaps	–	–	–	–	NS	0.003	0.037	0.004
Expanded canopy gap area	–	–	–	–	NS	0.016	NS	0.048
Vertical structure								
Ratio of sub-canopy to canopy basal area	NS	NS	NS	NS	NS	0.022	NS	0.031
Large tree density (⩾30 cm DBH)	NS	0.033	0.035	0.015	NS	0.022	0.009	0.008
Maximum height	NS	NS	NS	NS	NS	NS	NS	NS
Standard deviation of tree height	NS	NS	NS	0.021	NS	NS	NS	NS
Understory structure								
Intolerant hardwood sapling density (2–9.9 cm DBH)	NS	NS	NS	NS	NS	0.032	0.011	0.002
Shade-tolerant conifer sapling density (2–9.9 cm DBH)	NS	NS	NS	NS	NS	NS	NS	NS
High shrub density (2–9.9 cm DBH)	NS	NS	NS	NS	NS	NS	NS	NS
Deadwood structure								
Standing snag density (⩾10 cm DBH)	NS	NS	NS	NS	NS	NS	NS	NS
Standing snag basal area (⩾10 cm DBH)	NS	NS	NS	NS	NS	NS	NS	NS
Downed log volume	–	–	–	–	NS	NS	NS	NS

vs 1/3 partial cut and (2) controls vs 2/3 partial cut in pure aspen stands, and (1) controls vs dispersed cut and (2) controls vs gap cuts in mixed aspen stands. Normality of residuals and their random distribution in relation to predicted values were visually assessed. When these assumptions were not met, a square root transformation was used. Bar plots with mean ± 95% confidence intervals were used in all figures to illustrate the interval estimate of the estimated population parameter.

We first tested for differences between controls (mature stands) and partial harvesting treatments in terms of structural attributes (eighteen in total). We then evaluated the performance of partial harvesting treatments in terms of (1) *number of structural attributes of natural controls maintained*; that is, the number of attributes whose values were not statistically different between controls and partial harvesting treatment; (2) *accelerated stand development*; that is, attributes whose values were statistically different from controls and progressed toward old-growth aspen stand characteristics and (3) *undesirable changes*, or attributes whose values were statistically different from controls but did not progress toward old-growth aspen stand characteristics.

3. Results

3.1. Characteristics of old-growth trembling aspen-dominated boreal mixedwoods

Old-growth aspen stands are characterized by a high percentage of canopy gaps, multiple canopy layers and high structural variability in both the overstory and the understory layers (see Table 1 for ranges of values and references). Old-growth stands differ from younger or earlier successional stands by their lower total tree density, and particularly that of intolerant hardwoods, and lower stand basal area. Density, basal area and volume of shade-tolerant conifers, large trees, trees with heart rot, large snags and downed logs are higher in old-growth stands relative to those values observed in younger stands (Table 1).

3.2. Structural attributes of pure aspen and mixed aspen stands in relation to partial harvesting treatments

Prior to treatment application, there were no statistically significant differences among treatments in terms of stand density of live trees, stand basal area of live trees, snag density and snag basal area (results not shown).

3.2.1. Horizontal structure

Twelve years after harvesting of pure aspen stands, the significant initial reductions in total stand density and intolerant hardwood tree density (stems ⩾ 10 cm DBH) induced by harvesting were found to be statistically significant in the 2/3 partial cuts only (Table 2, Fig. 1A and B). In mixed aspen stands, total stand and intolerant hardwood tree densities were initially similar between controls and dispersed cuts, but 12 years after harvesting both densities were significantly lower in the dispersed cuts. Twelve years after treatment application, the 400 m^2 gap cuts had significantly lower stand and intolerant hardwood densities than the

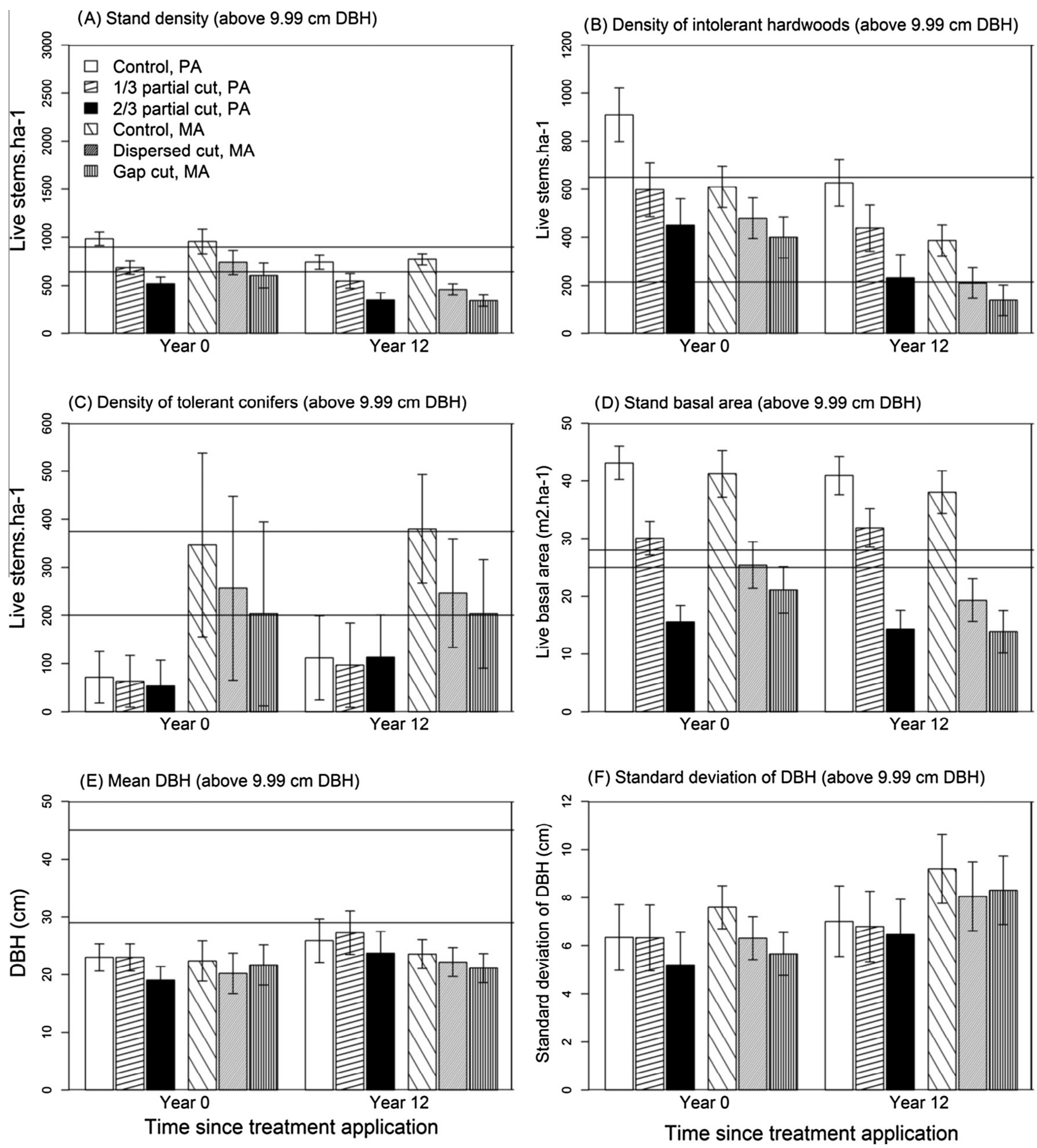

Fig. 1. Comparisons of stand attributes associated with horizontal structure among six partial harvesting treatments in two stand types. Note: Number of experimental units, $n = 9$; Error bars represent mean ± 95% confidence interval; PA: pure aspen stands and MA: mixed aspen stands. Two parallel horizontal lines represent the upper and lower ranges of old-growth structure (Table 1); Parallel lines not shown in figure F because of absence of reference values in the literature.

controls (Table 2, Fig. 1A and B). In both stand types, tolerant conifer density remained similar across treatments over the twelve year period. Again, in both stand types, the initial significant reductions in basal area induced by harvesting remained significant 12 years after harvesting (Table 2, Fig. 1C and D). At that time, stand basal area of pure aspen stands was 40.9 ± 3.3 (mean ± 95% confidence interval), 31.8 ± 3.3 and 14.3 ± 3.3 $m^2\ ha^{-1}$ in controls, 1/3 and 2/3 partial cuts respectively. In mixed aspen stands, the average stand basal area was 38.0 ± 3.7, 19.3 ± 3.7 and 13.9 ± 3.7 $m^2\ ha^{-1}$ in controls, dispersed cuts and gap cuts respectively (Fig. 1D). In both stand types, no differences in average tree DBH were found between harvesting treatments and controls, regardless of period since harvesting (Table 2 and Fig. 1E). Twelve years after harvesting, quadratic mean DBH was lower in 2/3 partial cuts than in controls of pure aspen stands and also lower in gap cuts than in controls of mixed aspen stands (Table 2 and Fig. 1E). The significant initial reductions in tree DBH size variability (standard deviation of tree DBH) in 400 m^2 gap cuts were no longer significant 12 years after treatment application (Table 2 and Fig. 1F).

3.2.2. Canopy gaps

Over all 250 m transects, average canopy gap length ranged from 3.3 to 12.1 m with a maximum value of 48.9 m observed in a gap cut of mixed aspen stands. Twelve years after harvesting of pure aspen stands, the percentage of canopy gaps and average expanded canopy gap area were larger in the 2/3 partial cuts than in controls whereas no difference was observed between controls and the 1/3 partial cuts for either attribute. In pure aspen stands, percentage of canopy gaps (mean ± 95% confidence intervals) were 18.3 ± 5.7, 21.2 ± 5.7 and 53.0 ± 8.8 %, in controls, 1/3 and 2/3 partial cut treatments, respectively (Table 2 and Fig. 2A, B). Twelve years after harvesting of mixed aspen stands, gap cuts had a higher percentage of canopy gaps and larger average expanded canopy gap area than controls. Only the percentage of canopy gap was found to be significantly higher in the dispersed cuts than in controls. In mixed aspen stands, percentages of canopy gaps (mean ± 95% confidence intervals) were 23.1 ± 6.7, 38.6 ± 8.5 and 61.3 ± 11.5 % in controls, dispersed and gap cut treatments, respectively (Table 2 and Fig. 2A, B).

3.2.3. Vertical structure

The sub-canopy to canopy basal area ratio was found to be significantly higher relative to controls in the 2/3 partial cuts of pure aspen stands and in the gap cut treatment in mixed aspen stands 12 years after treatment applications (Table 2 and Fig. 2C). The density of large trees, relative to controls, was reduced in the 2/3 partial cuts of pure aspen stands and in the dispersed and gap cuts of mixed aspen stands (Table 2 and Fig. 2D). No differences in maximum tree height were found between any partial harvesting treatment when compared with their respective controls (Table 2 and Fig. 2E). Tree height size variability (standard deviation of tree height) in 400 m^2 gap cuts was significant both initially following treatment and 12 years later (Table 2 and Fig. 2F).

3.2.4. Understory structure

Twelve years after harvesting, significantly higher densities of intolerant hardwood saplings were found in the 2/3 partial cuts than in controls of pure aspen stands and in dispersed and gap cuts than in controls of mixed aspen stands (Table 2 and Fig. 3A).

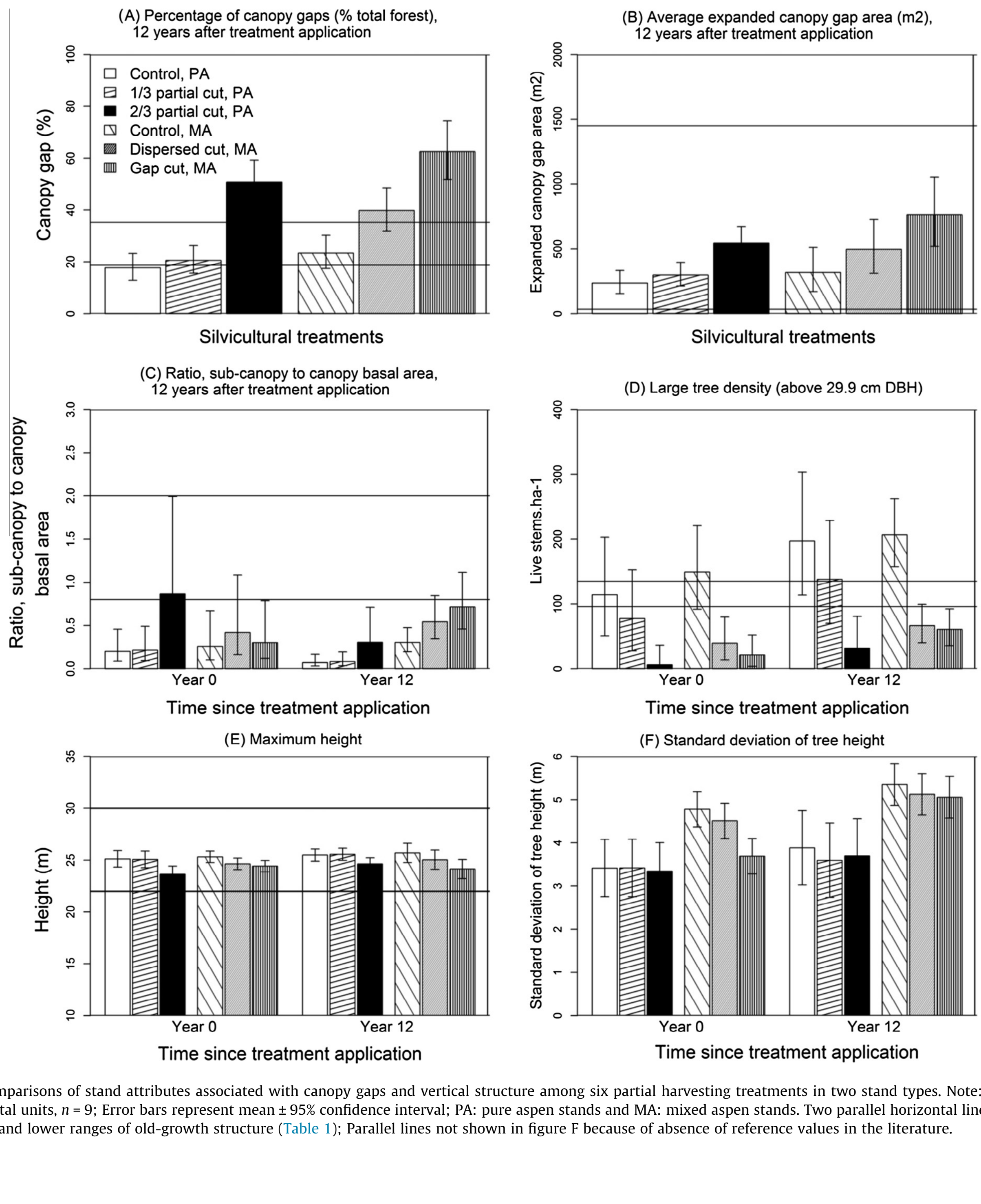

Fig. 2. Comparisons of stand attributes associated with canopy gaps and vertical structure among six partial harvesting treatments in two stand types. Note: Number of experimental units, $n = 9$; Error bars represent mean ± 95% confidence interval; PA: pure aspen stands and MA: mixed aspen stands. Two parallel horizontal lines represent the upper and lower ranges of old-growth structure (Table 1); Parallel lines not shown in figure F because of absence of reference values in the literature.

Conifer sapling densities were similar across treatments in both pure aspen and mixed aspen stands (Table 2, and Fig. 3C). Over the 12 year period, sapling density of both intolerant hardwoods and shade tolerant conifers increased in all treatments of both stand types (Fig. 3A and C). Twelve years after treatment application, a similar high shrub density was found among treatments of pure aspen stands, but higher in gap cuts (not statistically analyzed) than controls of mixed aspen stands (Table 2 and Fig. 3E).

3.2.5. Snags and downed logs

In both pure aspen and mixed aspen stands, snag density, snag basal area and downed log volume were similar across treatments. Snag density and basal area increased over the 12 year post-treatment period in both stand types. In pure aspen stands, total downed log volumes were 134, 94 and 91 $m^3\ ha^{-1}$ in controls, 1/3 and 2/3 partial cut treatments, respectively, whereas in mixed aspen stands, downed log volumes were 107, 119 and 156 $m^3\ ha^{-1}$ in controls, dispersed and gap cut treatments, respectively (Table 2, Fig. 3B, D and F).

4. Discussion

The principal aim of this study was to identify quantifiable structural attributes of old-growth trembling aspen-dominated stands in the boreal mixedwood forest in order to evaluate the potential of partial harvesting to enhance the development of these

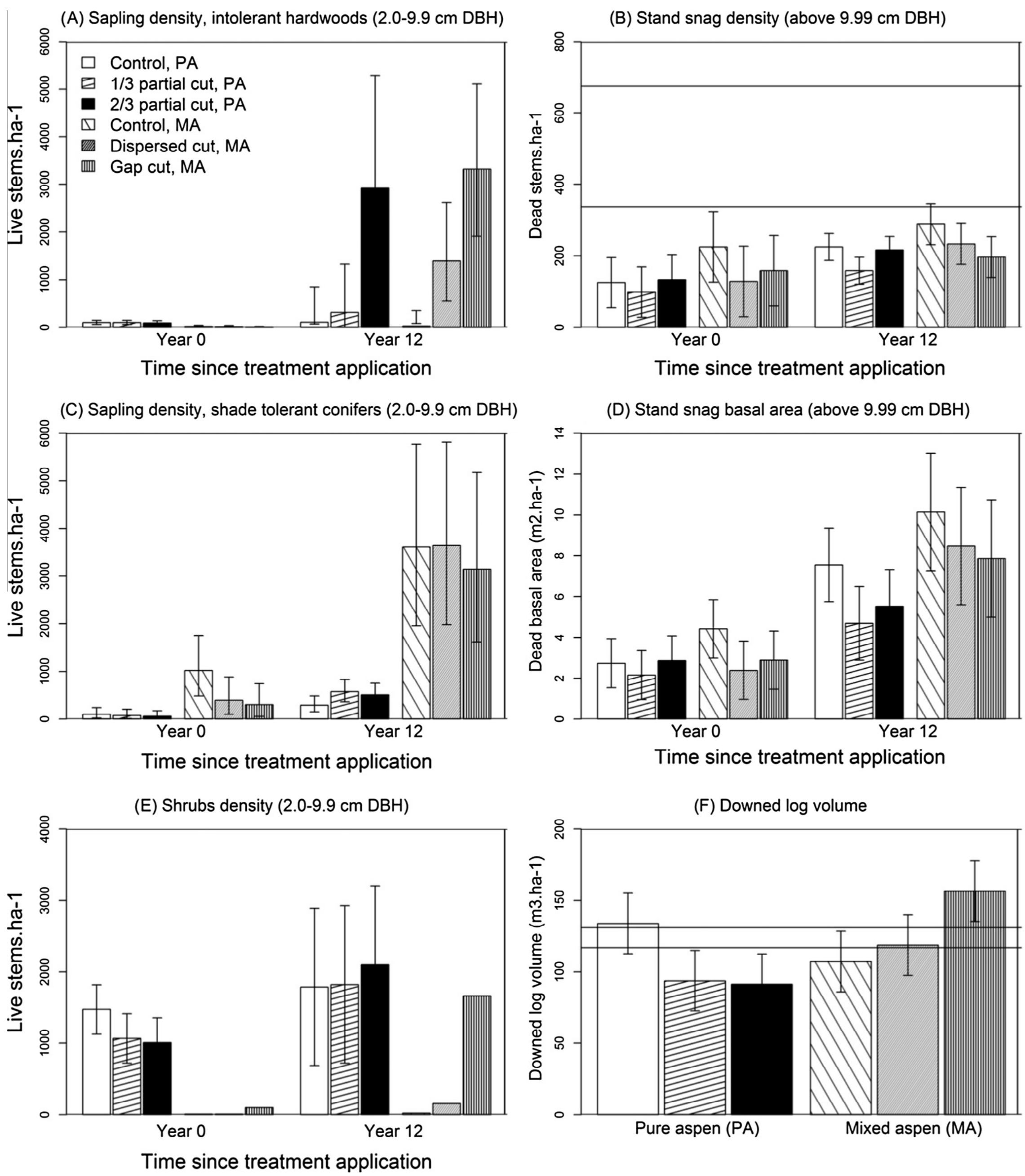

Fig. 3. Comparisons of stand attributes associated with understory and deadwood structure among six partial harvesting treatments of two stand types. Note: Number of experimental units, $n = 9$, Error bars represent mean ± 95% confidence interval; PA: pure aspen stands and MA: mixed aspen stands. Two parallel horizontal lines represent the upper and lower ranges of old-growth structure (Table 1); Parallel lines not shown in figures A, C, D and E because of absence of reference values in the literature. No statistical analysis was done on high shrub density in mixed aspen stand (figure E).

attributes in mature even-aged stands. The results of this study indicate that partial harvesting retained many of the structural attributes of mature aspen stands (untreated controls). However, twelve year after partial harvesting, the resulting stands present few of the attributes that characterize old-growth aspen stands.

4.1. Characterization of old-growth forests, a global perspective

Bauhus et al. (2009) defined old-growth forests as "a subset of primary forests that develop only under a limited set of circumstances, mostly associated with long periods without major natural disturbances". The old-growth forest has also been defined by a range of structural attributes and processes that illustrate a complex stand structure in both horizontal and vertical dimensions (see details in Spies and Franklin, 1988, 1991; Franklin and Van Pelt, 2004; Zenner, 2004; Bauhus et al., 2009; Burrascano et al., 2013). However, the typical old-growth attributes demonstrated by the above studies do not necessarily articulate the old-growth stage of boreal forests (Kneeshaw and Gauthier, 2003; Bergeron and Harper, 2009). Boreal forests in North America are associated with lower species richness, shorter-lived pioneer species, smaller tree sizes and slower decomposition processes than forests in temperate and tropical biomes (Kneeshaw and Gauthier, 2003; Bergeron and Harper, 2009); hence, the interest in ecosystem-specific indicators of "old-growthness".

4.2. Characterization of old-growth trembling aspen boreal mixedwoods

Large trees in old-growth aspen stands are generally longer-than-average survivors of the initial aspen cohort, but because aspen and other tree species of the Canadian boreal forest rarely grow into stands that could be described as majestic or "cathedral-like", as do some stands in more temperate forests (Franklin et al., 1981; Kneeshaw and Gauthier, 2003), old-growth aspen forests tend to deviate from the conventional image of what constitutes old-growth. Boreal aspen mixedwoods of stand-replacing fire origin are considered to evolve to an old-growth stage beginning around 100 years after stand initiation, a phase corresponding with increased density-independent mortality of the even-aged, post-fire cohort (Kneeshaw and Gauthier, 2003; LeBlanc, 2014). Senescence of the initial cohort could start even earlier (Pothier et al., 2004), depending on site productivity and regional factors (Frey et al., 2004). Individual tree or group mortality creates canopy gaps of various sizes (Kneeshaw and Bergeron, 1998; Hill et al., 2005) allowing recruitment of both shade-intolerant hardwoods (Cumming et al., 2000; LeBlanc, 2014) and tolerant conifers (Bergeron, 2000), depending on gap size, conifer seed sources and conifer presence in the understory (Greene et al., 1999). Hence, trembling aspen can maintain its dominance in late-successional stages by persistent regeneration recruitment, even in small gaps (Cumming et al., 2000; Bergeron et al., 2014; LeBlanc, 2014). These processes can result in uneven-aged stands with multiple cohorts of aspen as well as shade-tolerant coniferous species (Frelich and Reich, 1995; LeBlanc, 2014). Bergeron (2000) found tree ($\geqslant$10 cm DBH) density and basal area to be lower in old-growth aspen stands (100–200 years) than in mature even-aged aspen stands. The lower tree density and basal area in these old-growth stands are due at least in part to (1) self-thinning or density dependent mortality of the aspen cohort, (2) initiation of stand break-up due to senescence, (3) slow growth rates of understory conifers (balsam fir and spruces), and (4) possible competitive effects of woody shrubs and other understory vegetation on tolerant conifer establishment and growth in gaps (Bergeron, 2000; Frey et al., 2004; Pothier et al., 2004). These processes are not unique to boreal aspen-dominated mixedwoods, but obviously the dynamics and timing of similar processes and resulting structures will differ among forest types and regions (e.g., Franklin et al., 2002; Keeton et al., 2007) for mature and old-growth riparian forests in the Adirondack Mountains of upstate New York).

In natural even-aged stands, like those in this study, causes and rates of tree mortality change with successional phase from disturbance-induced mortality to self-thinning, and finally, senescence (Lee et al., 1997). Dynamics of snags and downed logs often follow a "U shaped" successional pattern with higher biomass in young and older stands (Harmon et al., 1986; Brais et al., 2005). Increased abundances of snags and downed logs are associated with stand break up. However, as a result of relatively slow decomposition rates in the boreal forest (Laiho and Prescott, 2004; Brais et al., 2006), downed logs in mature boreal stands include both legacies from pre-fire events and the most recent stand replacing fire (Lee et al., 1997). It is expected that old-growth boreal stands should therefore be characterized by a wide range of downed log sizes and decay states (Lee et al., 1997; Kuuluvainen et al., 2001).

Kneeshaw and Burton (1998) and Kneeshaw and Gauthier (2003) proposed two measurements to characterize the progression of cohort replacement in over-mature stands: the cohort basal area ratio (CBAR) and the cohort basal area proportion (CBAP). These measurements assume that the first even-aged tree cohort still occupies the upper canopy. Mortality of this first cohort promotes recruitment of a second and third tree cohort into canopy gaps that will form the intermediate (sub-canopy) and regeneration layers. The CBAR and CBAP reflect the size and density of saplings relative to remnants of the first cohort. However, these ratios require the identification of the cohort to which each individual stem belongs, which is time consuming (Harper et al., 2003). To address this limitation, Lee et al. (2000) proposed a simpler ratio of basal area of sub-canopy trees (intermediate and suppressed) over basal area of canopy (dominant and co-dominant) trees defined by DBH size, irrespective of tree age. The ratio of sub-canopy to canopy basal area reflects the heterogeneity of stand tree size, a recognized attribute of old-growth/late successional stands (e.g., Kneeshaw and Gauthier, 2003; Zenner, 2004; Bauhus et al., 2009). It also provides an indication of the degree of transition from a typical unimodal diameter distribution of the initial cohort toward a broader distribution as mortality occurs in the canopy layer and the sub-canopy increases in importance.

Fire cycles are generally longer in the eastern mixedwood boreal forest than in the boreal plains of western Canada with annual burn rates (%) estimated by Boulanger et al. (2012) to range from 0.005 to 0.110 in the east and 0.013 to 0.634 in the western mixedwood forest. Therefore, the presence of late-successional species such as balsam fir and eastern white cedar could also be used as an indicator of old-growth stands in eastern boreal mixedwoods. While not adapted for regenerating after fire, balsam fir regenerates well by seed under a variety of conditions and can be found in early successional stands; therefore, size of balsam fir trees as well as its abundance in aspen-dominated mixedwood stands is important. In the case of cedar, its frequency of occurrence in the eastern boreal mixedwood landscape is fairly low so old-growth stands will not necessarily contain the species, especially if there are no proximate mature stands to act as seed sources. However, because cedar relies largely on well-decomposed logs for establishment (Simard et al., 2003), it generally recruits decades after stand-replacing fires (Bergeron, 2000) so, when present, cedar is generally a very good indicator that a mixedwood stand is old.

Crites and Dale (1998) and Haeussler et al. (2007) also demonstrated the importance of understory vegetation (vascular and non-vascular plants) and fungi in defining old-growth boreal mixedwoods. They argued that canopy gaps in old-growth stands facilitate development of a richer understory composition than that found under the closed canopy of younger stands.

Based on these considerations, the identification and characterization of old-growth boreal aspen mixedwoods should be based on several structural attributes (Table 1). These include percentage of canopy gaps, tree size-variability, presence of late-successional species, diversity of tree and non-tree species, large tree density and downed log abundance.

4.3. Potential of partial harvesting to enhance the development of old-growth attributes in mature even-aged stands

4.3.1. Pure aspen stands

The 1/3 partial cuts prioritized removal of smaller and suppressed stems to emulate tree mortality associated with self-thinning (Harvey and Brais, 2007). The 1/3 partial cuts maintained 17 attributes of untreated mature stands (controls) and reproduced one old-growth attribute of lower stand basal area compared to control stands (Table 3). This treatment created few and small canopy gaps relative to values reported for old-growth stands (Kneeshaw and Bergeron, 1998; Hill et al., 2005). Hence, canopy opening was insufficient to enhance sapling recruitment of both shade-intolerant and tolerant saplings (Fig. 3A and C) or to increase residual tree growth (Bose et al., 2014a). Therefore, 1/3 partial cuts resulted in a lower ratio of sub-canopy to canopy basal area than the ratio reported by Lee et al. (2000) for old-growth aspen stands. By removing mostly small trees, the treatment also simplified stand structure by allowing co-dominants and dominants of the initial cohort to fully occupy the canopy growing space and inhibiting recruitment of a new cohort of stems (O'Hara, 2001). As a result, variability of horizontal and vertical tree size (standard deviation of DBH and height, respectively) was not increased in 1/3 partial cuts 12-years post-treatment. However, the treatment maintained an average of 138 large trees ha^{-1}, or 17% of total stand density, which is within the range for old-growth aspen stands proposed by Lee et al. (2000). In addition, the 1/3 partial cuts maintained snag and log abundances within values observed in untreated controls. Hence, a light, low thin will clearly delay stand transition from even-sized hardwood dominance to a mixedwood composition with greater vertical variability, but will maintain the potential of these stands to evolve toward more structurally complex old-growth stands.

According to O'Hara (2001), the first step to increasing structural variability using partial harvesting is to create growing space for new cohorts. The 2/3 (heavy crown) partial cuts, where dominant and co-dominant trees were primarily harvested to emulate senescence mortality or stand break-up (Harvey and Brais, 2007), created more growing space than what is reported for aspen-dominated old-growth stands. The percentage of canopy gaps (44–62%) observed 12 years after treatment was considerably higher than values (18.7–40.9 %) reported by Kneeshaw and Bergeron (1998) for old-growth aspen stands and promoted higher sapling recruitment of intolerant hardwoods than that reported by these authors. The 2/3 partial cuts did not promote the ratio of sub-canopy to canopy basal area reported for old-growth aspen stands by Lee et al. (2000), but nevertheless caused a significant increase relative to untreated mature stands (controls). The current sapling layer of 2/3 partial cuts showed the potential of this treatment to further increase the ratio of sub-canopy to canopy basal area in the following years (Fig. 2C). In 2/3 partial cuts, large tree density was lower relative to large tree density of old-growth aspen stands (Lee et al., 1997; Bergeron, 2000). Nonetheless, like the 1/3 cuts, the 2/3 partial cuts maintained many (10) of the attributes of untreated mature stands (controls), such as shade-tolerant conifer tree density, DBH variability, maximum tree height and tree height variability, density of shade-tolerant conifer saplings, shrub density and snag and log abundance (Tables 2 and 3). In the short-term, the "stand break-up" condition (300 aspen stems ha^{-1}, 15 m^2 ha^{-1} BA) artificially generated by the 2/3 partial cuts may reflect senescence plus the exacerbating effects of severe forest tent caterpillar outbreaks on overstory aspen mortality and sapling recruitment rather than stand break-up alone (see in Man et al., 2008b; Moulinier et al., 2011). This treatment resulted in a higher percentage of canopy gaps and recruitment of intolerant hardwood saplings than old-growth aspen dominated stands and may set back successional development (Table 3).

4.3.2. Mixed aspen stands

In mixed aspen stands, dispersed or diffuse partial cuts were applied to emulate individual-level tree mortality. This treatment could be considered a free thin in which merchantable stems of all size classes were removed. The basal area removed was between that of the 1/3 and 2/3 partial cuts conducted in pure aspen stands and resulted in canopy gap occupancy (32–48%) close to that reported for old-growth stands. However, the dispersed cut did not create a ratio of sub-canopy to canopy basal area within the range of old-growth aspen stands reported by Lee et al. (2000). Nonetheless, the dispersed cut maintained 12 attributes of untreated mature stands (controls) and accelerated succession in terms of canopy gap percentage, expanded canopy gap area and intolerant hardwood density (Table 3). The treatment did not increase, but maintained tree size variability (standard deviation of DBH and height) of mature untreated control stands. However, the dispersed cut reduced the density of large trees: the average of 66 large trees ha^{-1}, 4% of stand density, is much lower than values reported for old-growth aspen stands (Lee et al., 2000; Schieck et al., 2000). Finally, mean volume of downed logs (115 m^3 ha^{-1}), while not significantly different from untreated controls, was close to aspen old-growth volumes (117–131 m^3 ha^{-1}) reported by Lee et al. (1997). By creating canopy gaps similar to old-growth aspen stands and by promoting recruitment of both intolerant hardwoods and tolerant conifers, this treatment may produce a structurally complex stand in following years.

Similar to 2/3 partial cuts in pure aspen stands, 400 m^2 gap cuts in mixed aspen stands produced higher canopy gap occupancy than values reported by Kneeshaw and Bergeron (1998) and Hill et al. (2005) for old-growth aspen stands. Expanded gap areas were also higher, in part due to subsequent windthrow. This high percentage of canopy gaps resulted in higher sapling densities of intolerant hardwoods relative to those for old-growth stands reported by Kneeshaw and Bergeron (1998). Twelve years after harvesting, the range of the ratio of sub-canopy to canopy basal area was 0.46–1.11, which is the highest among all treatments and falls at least partly within the range of old-growth aspen stands (0.8–2.0). Similar to the 2/3 partial cut in pure aspen stands, the gap cut maintained 10 attributes of untreated mature stands (controls) and accelerated stand development in terms of expanded canopy gap area, ratio of sub-canopy to canopy basal area and intolerant hardwood density (Table 3). Similar to dispersed cuts, large tree density was lower in gap cuts relative to densities reported for old-growth aspen mixedwoods (Lee et al., 2000; Schieck et al., 2000). Like the other partial harvesting treatments, gap cuts maintained levels of deadwood (snags and downed logs) comparable to those of mature aspen stands (untreated controls) and the quantity of deadwood was comparable to deadwood in old-growth aspen forests (Table 1). These results of non-negative effects of partial harvesting on deadwood are contrary to some other studies conducted elsewhere in North America (e.g., McGee et al., 1999; Angers et al., 2005; Keeton, 2006).

Table 3
Summary of effects of partial harvesting treatments in terms of promoting structural attributes of old-growth aspen stands or accelerating succession.

Stand types	Treatments	No. of structural attributes of natural controls maintained[a]	Accelerated stand development in terms of...[b]	Undesirable changes in terms of...[c]	Effects on succession
Pure aspen	1/3 partial cut (low, light thinning, 33% BA removal)	17	Lower stand basal area	–	Removing smaller stems may prolong simple, even-sized structure
	2/3 partial cut (high, heavy thinning, 61% BA removal)	10	Greater expanded gap area, higher ratio of sub-canopy to canopy basal area, lower hardwood tree density	Too high percentage of canopy gaps and hardwood sapling density and too low stand density, stand basal area and large tree density	Strongly favors recruitment of intolerant hardwood saplings which may set back canopy succession
Mixed aspen	Dispersed cut (free thinning, 45% BA removal)	12	Higher canopy gap percentage, greater expanded canopy gap area and lower hardwood tree density	Too low stand density, stand basal area and large tree density	Should accelerate stand development of more complex structure in terms of canopy gaps and both intolerant hardwood and tolerant conifer sapling recruitment
	400 m^2 gap cut (54% BA removal)	10	Greater expanded gap area, higher ratio of sub-canopy to canopy basal area and lower hardwood tree density	Too high percentage of canopy gaps and hardwood sapling density and too low stand density, stand basal area and large tree density	Strongly favors recruitment of intolerant hardwood saplings which may set back canopy succession

[a] Total number of attributes evaluated = 18. Number of structural attributes of natural controls maintained = number of attributes that are not statistically different between control and partial harvesting treatments.
[b] Accelerated stand development in terms of... = attributes whose values are statistically different from controls and progressed toward old-growth aspen stand characteristics.
[c] Undesirable changes in terms of... = attributes whose values are statistically different from controls but did not progress toward old-growth aspen stand characteristics.

4.4. Management implications

The structural and, potentially, compositional differences between a 60 year old, even-aged, pure or mixed aspen-dominated stand and the same stands 60–100 years later are enormous. The latter, now old-growth, can be expected to contain fewer but larger stems, greater stem size variability, more canopy gaps of different sizes, multiple tree cohorts, more snags and downed log volume and, in the case of mixedwoods, a greater shade-tolerant conifer component in all layers. The presence of fewer but larger and older aspen stems alone has important implications in terms of habitat suitability, be it for cavity-nesting wildlife (Ouellet-Lapointe et al., 2012), arboreal lichens (Boudreault et al., 2002) or other forms of biodiversity. It is evident then that managing aspen-dominated mixedwood forests solely on 50–80 year rotations will result in a loss of ecosystem (or forest stand type) diversity and habitat diversity at the landscape scale. However, with its prolific suckering, fast growth and relatively short lifespan, aspen is perfectly adapted to and generally managed under an even-aged, coppice system. This said, from a forest ecosystem management viewpoint, managing a portion of aspen mixedwoods to develop into more complex stands that contain key structural and compositional attributes of old-growth is not only justifiable, but there is considerable support to indicate that it is also biologically feasible (Man et al., 2008a; Solarik et al., 2010; Bose et al., 2014a). That is, aspen can biologically perform – regenerate, grow well and live long enough to be harvested later – following treatments other than large-gap coppice. Moreover, this consideration of possible alternative silvicultural approaches joins the emerging concept of managing forests for complexity (Messier et al., 2013).

If partial harvesting has its place in boreal mixedwood ecosystems, approaches used to enhance old-growth characteristics should be guided by several factors, notably: (1) composition and structure of stands to be treated (probably most importantly, with respect to the conifer component); (2) ranges of structural and compositional old-growth objectives (how much of what in how many years); (3) a good understanding of tree and understory responses to a variety of partial harvesting intensities and gap sizes under a range of initial stand conditions; and (4) a measure of the implications of different silvicultural options on treatment costs and harvestable volumes at the stand and, cumulatively, management unit levels. While this study looked at medium-term outcomes of single commercial treatments in mature aspen-dominated stands, a variety of single- and multiple-entry options are probably available, particularly to managers working with an overabundance of aspen growing stock. Moreover, treatments should probably start earlier in stand development than those applied in this study.

Our results are largely artifacts of the specific treatments applied in the two studies and old-growth-oriented partial harvesting prescriptions for aspen-dominated mixedwood forests could incorporate explicit targets for a number of features. These could include, for example (and values are also examples): lower limits for residual merchantable aspen BA (ex. 40–50%; dispersed cut in our aspen mixedwood stand) and minimum number of large aspen stems to be retained per ha (ex. 15% of total stand density (Lee et al., 2000); range of harvest gap sizes (ex. 400–1600 m^2) (Bose et al., 2015) and specific thinning prescriptions for between gaps (ex. free thin 1 in 3 stems) (Haeussler et al., 2007); stem size limits on conifer removal (ex. retain stems $\leqslant$ 16 cm DBH); and protection measures for snags, dying stems and patches of dense conifer seedlings and saplings (Kneeshaw and Gauthier, 2003; Haeussler et al., 2007). This is clearly more complicated than clear-cutting, but well-trained operators who have been involved in partial harvesting experiments have demonstrated that these treatments can be done and, certainly, the short- to long-term outcomes and ecosystem services are considerably different.

The structural framework for identifying old-growth aspen-dominated mixedwoods (Table 1) is based on relatively few studies, evidence that there is still limited information on what actually constitutes old-growth in these stand types. Old permanent sample plots such as those used by LeBlanc (2014) are extremely precious and similar information may exist elsewhere in the boreal mixedwood (and in old boxes and filing cabinets). Certainly, there is a need for long-term (permanent) monitoring of unmanaged aspen mixedwoods. While the successional dynamics of aspen-dominated mixedwoods are reasonably well understood (for example, see Bergeron et al., 2014), the temporal specifics of characteristic stand development stages and transition phases are more elastic in nature and thus contribute to management concerns regarding anticipated outcomes of silvicultural treatments such as partial harvesting. Long-term monitoring of mixedwood silvicultural experiments is therefore also essential to validating novel management practises in these forests.

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