

Spatial analysis of response of trembling aspen patches to clearcutting in black spruce-dominated stands

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ABSTRACT

While expansion of intolerant hardwoods, including trembling aspen, has been recognized as a problem by boreal forest managers in eastern Canada, the problem has mostly been associated with the boreal mixedwood and, with a few exceptions, the spatial aspects of the phenomenon have not been well documented in the scientific literature. The objective of this study is to evaluate how the density and size of aspen patches influence the change in density, size and persistence of patches following clearcutting of black spruce forests in the claybelt region of northwestern Quebec. To do this, we finely interpreted: 1) aerial photos taken between 1970 and 1979 of 12 mature black spruce-dominated stands containing varying sizes and densities of aspen patches prior to being clearcut harvested and 2) aerial photos taken between 1992 and 1995 of the 12 resulting clearcuts, 11 to 18 years after harvesting. Sketch maps of pre- and post-harvest aspen presence were rasterized and changes in aspen patch size and cover were determined. As well, the probabilities of aspen colonization with increasing distance from pre-harvest patches were calculated for each site. Black spruce forests of the claybelt containing no aspen prior to harvesting are relatively resistant to aspen invasion. However, when forests do contain aspen patches with cover values $\leq 25\%$, almost 60% of these patches increase to a higher density class. Aspen patches less than 2 ha in area had about a 50% probability of disappearing following clearcutting whereas larger patches had about a 96% chance of persisting as a result of clearcutting. In the black spruce forest of the claybelt, thick organic layers appear to have a negative effect on aspen recruitment. Distances of regenerating aspen from pre-harvest patches suggest that recruitment from seed is more important than previously thought.

Key words: encroachment, trembling aspen, clearcutting, black spruce, claybelt, aerial photography

RÉSUMÉ

Dans la forêt boréale de l'Est du Canada, l'augmentation de la proportion de feuillus de lumière par rapport aux peuplements d'origine (enfeuilletement), est reconnue comme un enjeu par les gestionnaires forestiers. Dans la littérature scientifique, l'enfeuilletement a été associé essentiellement à la forêt mélangée et les aspects spatiaux du phénomène sont relativement peu documentés. L'objectif de cette étude était d'évaluer l'influence de la coupe totale sur la densité, la taille et la persistance des grappes de peuplier faux-tremble dans des forêts d'épinette noire de la ceinture d'argile du Nord-Ouest du Québec. Pour ce faire, nous avons interprété: 1) des photographies aériennes datant de 1970 à 1979 de douze pessières noires ponctuées de grappes de tailles et de densités variables de peuplier faux-tremble et 2) des photographies aériennes datant de 1992 à 1995 composées des mêmes 12 territoires forestiers, 11 à 18 ans plus tard suivant une coupe totale. Les croquis de cartes des présences pré- et post-récolte de peupliers ont été numérisés en format raster et les changements de superficie et du couvert des grappes de peuplier ont ensuite été déterminés. De plus, les probabilités de colonisation de peuplier en fonction des distances des grappes de peuplier pré-récolte ont été calculées pour chaque site. Les résultats suggèrent que la pessière pure (0% de peuplier) est relativement réfractaire à l'enfeuilletement. Toutefois, lorsque les forêts contenaient une proportion de peuplier $\leq 25\%$, nous avons observé une augmentation de la classe de recouvrement dans presque 60% des cas. Les grappes de peuplier plus petites que 2 ha avaient environ 50% de probabilité de s'éteindre suite à la coupe totale tandis que les grappes de plus grande dimension avaient environ 96% de chance de persister suite à la coupe totale. Dans la pessière noire de la ceinture d'argile, les couches organiques épaisses semblent affecter négativement le recrutement du peuplier. Les distances séparant les peupliers en régénération des grappes pré-récolte suggèrent que le recrutement par graine est plus important qu'attendu.

Mots-clés : enfeuilletement, peuplier faux-tremble, coupe totale, pessière noire, ceinture d'argile, photographie aérienne

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Introduction

Natural disturbance regimes, dominated by fire and insect outbreaks, have historically controlled the composition and structure of boreal forest mosaics (Bergeron *et al.* 2001). Over the last several decades, however, forest management activities, particularly harvesting, have replaced these natural agents as the principal disturbance in the southern part of the eastern boreal forest (Carleton 2000) and, over the

long term, human intervention has resulted in a considerable increase in the proportion of intolerant hardwoods in this landscape (Bergeron *et al.* 2004).

Trembling aspen (*Populus tremuloides* Michx.) is an early successional species that regenerates vigorously after fire, notably by root suckering in stands where it is already present (Schier 1973, Brown and DeByle 1987, Johnstone and Chapin 2006). Because it is shade-intolerant and a generally short-lived species, in the absence of disturbance, aspen gradually dies and drops out of the forest as longer-living, shade-tolerant species capture these sites. Clearcutting has also been shown to favour aspen suckering (Perala 1974, Doucet 1989, David *et al.* 2001) by mechanisms similar to those induced by fire: suppression of apical dominance of commercial-sized stems, physical damage of surface roots (Fraser *et al.* 2004) and increases in summer soil temperatures (Bella 1986). Suckers tend to project out radially from the central point of the parent stem (Comtois and Payette 1987); reported distances of suckering from parent stems vary from 14.3 m (47 ft; Day 1944) to “about 20 m” (Shepperd 2001) and “more than 30 m” (Peterson and Peterson 1992). These distances may, however, greatly underestimate the potential rooting distance of aspen clones; in a study by Namroud *et al.* (2005), median clonal dimensions in two mixedwood stands were 19 m and 29 m but intergenerational maxima were measured to 104 m and 74 m, respectively.

Aspen has been a part of the natural forest mosaic of the southern boreal mixedwood forest of Quebec and Ontario for centuries. Favourable climatic conditions, relatively short fire cycles and proximity of seed sources to disturbed areas have

all likely contributed to maintaining aspen in these landscapes. However, its presence in the more northerly black spruce forests of the claybelt region of Quebec and Ontario was likely restricted mostly to localized upland sites prior to large-scale industrial forest harvesting. While Chen and Wang (2006) found virtually no increase in hardwood density following group seed tree and careful logging in lowland black spruce forests of the Ontario claybelt, other studies in northeastern Ontario (Brumelis and Carleton 1988, Carleton and MacLellan 1994, Carleton 2000) and northwestern Quebec (Grondin *et al.* 2003a, Laquerre *et al.* 2009) confirm that aspen's northerly expansion into the black spruce forest is indeed occurring and is a relatively recent, industrially driven phenomenon.

In this context, we are interested in developing a better understanding of the degree of persistence and the spatial dynamics of aspen patches following forest harvesting. The object of this study was then to characterize the extent of intolerant hardwood expansion in black spruce-dominated stands, interspersed with varying-sized patches of trembling aspen, following clearcutting in the claybelt of northwestern Quebec. According to several authors (Brumelis and Carleton 1988, Harvey and Bergeron 1989, Carleton and MacLellan 1994), trembling aspen propagates particularly aggressively on fine-textured surface deposits. Our hypothesis in this regard was that clearcutting of black spruce stands on mesic clay soils, punctuated with small patches of trembling aspen, would result in an increase in aspen density and in the area of these patches.

Material and Methods

Study area

The study region is located between 48.5°N and 49.5°N around the interface between the western balsam fir–white birch and black spruce–feathermoss biogeoclimatic subdomains (Bergeron *et al.* 1998). The area is also situated in the great claybelt of northwest Quebec, a vast clay plain that inclines gently northward toward James Bay and whose glaciolacustrine sediments are vestiges of the ancient proglacial Lake Ojibway (Vincent and Hardy 1977). In the northwestern part of the study area, surficial deposits are composed of stony clays resulting from a readvancement of the Cochrane glacier into the clay deposits of Lake Ojibway (Hardy 1977). The forest is dominated by black spruce (*Picea mariana* [Mill.] BSP) with smaller portions of jack pine (*Pinus banksiana* Lamb.), aspen and balsam fir (*Abies balsamea* [L.]). Mean annual temperature is 0°C to -2.5°C. The growing season is about 150 days and total precipitation is 700 mm to 800 mm (Robitaille and Saucier 1998). Topography is generally flat and bogs, lakes and rivers are abundant. Large-scale industrial forest harvesting has been carried out in the study area since the 1970s. According to Bergeron *et al.* (2004), the transition between the two bioclimatic subdomains is principally controlled by the disturbance regime, specifically the size and the severity of fires. In the balsam fir–white birch domain to the south, the abundance of intolerant hardwoods, the presence of a complex hydrographical network, and landscape fragmentation by roads and agricultural land act as fire barriers and contribute to reduce the size and the severity of fires. The black spruce zone is characterised by severe crown fires that generally cover large areas.

Photo interpretation

Despite the increasing availability of satellite imagery and other remote sensing technologies, aerial photography has long been considered an ideal tool for detecting and illustrating changes in forest cover through time (Hart and Laycock 1996). According to Kadmon and Hanari-Kremer (1999) and Bierman *et al.* (2005), aerial photography provides the only information source that combines fine spatial resolutions, large-scale coverage and long-term vegetation monitoring potential. This study used panchromatic black and white aerial photographs to characterize the dynamics of hardwood (trembling aspen) expansion in the black spruce boreal forest region following industrial clearcutting.

Selection of sites and aerial photos

A search of forest maps and available aerial photos was first conducted in order to locate forested areas that had been aerial photographed both prior to and following clearcutting in order to obtain paired photos for each site. The first set of photos, part of a province-wide aerial photography campaign used for the first “decade inventory” conducted by the Quebec Ministry of Natural Resources and Wildlife (QMNRW) in the 1970s, illustrated original mature forest cover and was selected based on forest cover type and surficial deposit type. This latter information was obtained from more recent 1:20,000 forest ecosystem cover maps produced by the QMNRW (Grondin *et al.* 2003b). Black spruce-dominated stands containing less than 25% cover of trembling aspen and situated on mesic to subhydryc clay soils were selected because these sites were considered particularly susceptible to intolerant hardwood encroachment (Grondin *et al.* 2003a, Laquerre *et al.* 2009). The second set of aerial photos, part of the third decade inventory undertaken in the 1990s, illustrated the naturally regenerating cover following harvesting on these same sites. We established a minimal interval of ten years between the year of harvesting and the year the second set of photos was taken in order to obtain a clear signal of the regenerating vegetation. Sites that had received any post-harvest silvicultural treatment (site preparation, plantation, artificial seeding, precommercial thinning or cleaning) or that had burned since cutting were excluded. The 12 clearcuts subject to fine-scale photo-interpretation for this study occurred between the first and third decade inventory periods (Table 1).

Photo interpretation and sketch mapping

Sketch maps of forest cover prior to and following clearcutting were drawn from the aerial photos using a WILD ST4 mirror stereoscope (3× magnifying lenses). This was done using transparent tracing paper placed on the stereoscopic pairs of photos of pre- and post-harvest conditions. Roads, hydrographical features, cutover perimeter and zones containing trembling aspen (in and around the cutover) were traced by hand.

For the sketch maps representing original forest cover, variations in grey tones and texture of the stands were used to delineate different “objects” with precision. Aspen is difficult to distinguish from white birch (*Betula papyrifera* Marsh.) on 1:15 000 black and white aerial photographs; however, given the nature of the surficial deposit, birch was virtually absent in the areas studied.

For the sketch maps representing the return (post-harvest) cover, the identification of the young stands in the regeneration phase was more difficult. These recruiting stands are generally characterized by a paler grey tone. Moreover, the young crowns are often very dense and lack clear definition, giving the photographs a very uniform texture with little distinct pattern.

Digitization of sketch maps and probability of colonization

Using a high-precision scanner, maps were digitized and imported into Arc Map. The georeferencing function was used to overlay sketch maps on layers (shapefile format) of the QMNRW forest ecosystem maps. Control points corresponding to intersections and forks of roads and watercourses were used to rubber-sheet digitized sketch maps to other map layers. This geometric rectification provided spatial reference and harmonized the different scales (Fig. 1). Following this step, the perimeter of cutovers and aspen patches were redrawn on-screen in Arc Map and the aspen cover classes, based on an estimation of relative crown cover of aspen in the canopy, were entered into the data table. In order to evaluate the range of aspen colonization from pre-harvest patches, pre- and post-harvest sketch maps were then converted from vectorial to matricial (10 m × 10 m grid) format using the Spatial Analysis function of Arc Map and cells in the paired maps for each site were either tagged “1” for hardwood present or “0” for hardwood absent. Cells that were tagged 0 in the pre-harvest condition and 1 in the post-harvest condition were considered to have been colonized. Probability of colonization was determined for each cutover site by calculating the percentage of cells situated equidistant to aspen patches (in increments of 10 m) that were tagged as colonized. As well, all pre-harvest aspen patches (n = 50) were listed by size (ha) and classified as persistent or extinguished, based on presence or absence of aspen in post-harvest photos.

Table 1. Information concerning black and white panchromatic aerial photos used for study

Location (Township)	Photo year (before cut) ^a	Photo year (after cut)	Year of cut	Time between cut and post-cut photo (years)
Paradis	1974	1992	1976	16
Laberge	1974	1992	1976	16
Ligneris	1974	1992	1975	17
Casa Béardi	1972	1992	1975	17
Dalet	1974	1992	1981	11
Rainboth	1974	1992	1975	17
Bacon	1979	1992	1979	13
Coigny 1	1970	1995	1977	18
Coigny 2	1972	1992	1978	14
Coigny 3	1970	1995	1977	18
Coigny 4	1970	1995	1978	17
Bernetz	1970	1992	1976	16

^aAll photos were 1:15,000 scale except those of Coigny 1, 2, 3, 4 and Bernetz taken in 1970s at 1:20,000.

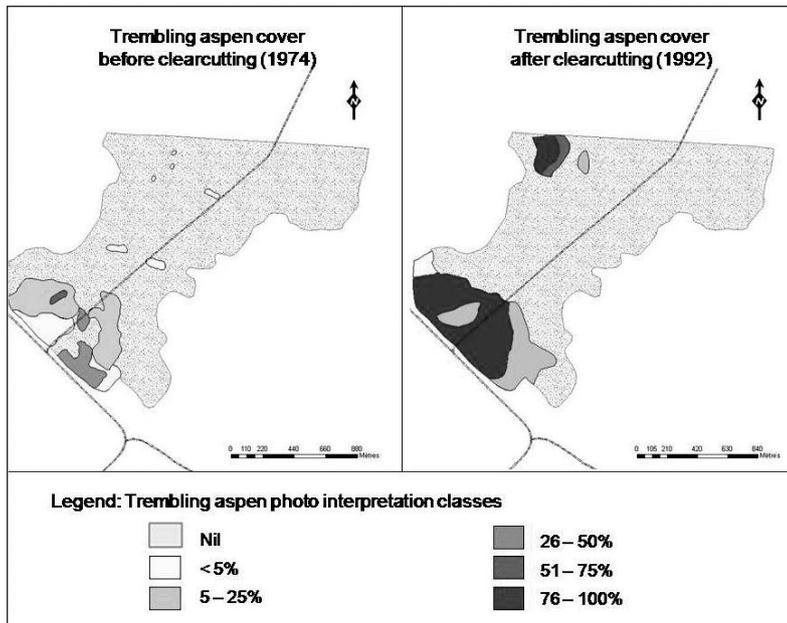


Fig. 1. Example of two sketch maps of aspen patches in Casa Bérardi site before and 17 years after clearcutting in 1975.

Field inventory

Because of the more nuanced vegetation signal on post-harvest aerial photos, field inventories of the 12 cutovers were conducted in order to validate photo interpretation. Circular regeneration plots (9 m², r = 1.69 m for hardwoods; 4 m², r = 1.13 m for softwoods) were placed along transects located to run through photo interpreted aspen patches in cutovers. Soil conditions (surficial deposit and organic matter thickness) were verified and measured and tree species were tallied by species and height class in 30% of 1300 plots and presence/absence of species noted in 70% of plots. This validation permitted correction of certain cover classes that were over- or underestimated in the photo interpretation and confirmed that all sites were on lacustrine clay soils. Once sketch maps were completed, percent cover of trembling aspen of each cluster was estimated and grouped into categories (Table 2).

Table 2. Photo interpretation cover classes of aspen patches

Class	Aspen cover (%)
0	Nil
1	<5
2	5-25
3	26-50
4	51-75
5	>75

Statistical analyses

Using the function Tabulate Area (Spatial Analysis – Zonal area), contingency tables of transitions from pre-harvest to post-harvest conditions were produced from overlays. Crossing these layers generated pairs corresponding to different possible transitions. The grids were then exported into Excel

in order to calculate changes of cover classes of aspen before and after clearcutting (increase, decrease or unchanged). Field inventory was summarized to explore whether aspen and black spruce were antagonistic in cutovers and whether organic matter depth influenced aspen presence.

Results

Transitions of cover classes of trembling aspen

Changes in cover classes of aspen before and after clearcutting are illustrated using stacked bar graphs for all 12 cutovers combined (Fig. 2). Each bar corresponds to an aspen cover class prior to harvesting and the stacked portions within each bar correspond to the cover classes after harvesting. As such, each bar represents the transition vectors associated with a pre-harvest cover class of aspen.

Greatest increases in cover class occurred in pre-harvest classes 1, 2 and 3 (<5% to 50%). Moreover, in many instances increments occurred by more than one class; for example, in cover class 2 (5% to 25% aspen), 22% of patch area increased to class 3 (26% to 50%), 22% increased to class 4 (51% to 75%) and 15% to class 5 (>75%) (Fig. 2). Where aspen was absent prior to harvesting (cover class 0), hardwood invasion occurred at a rate of 15% (Fig. 2, 3). For the pre-harvest aspen cover class 1 (<5%), 57% of the zone moved to a higher cover class whereas 43% was interpreted as absent. In patches of cover class 2 (5% to 25%), density increased to a higher class in 59% of cases, remained stable in 18% and decreased in 23% of cases. For aspen patches in cover class 3 (26% to 50%), 44% increased in density after harvesting, 35% remained stable and 20% decreased in aspen density. For the cover class 4 (51% to 75%), patches increased to the highest density class in only 12% of cases, while 86% remained stable within the same density class and only 2% decreased. Finally, patches in the highest density class (>75%) were essentially saturated and tended to remain stable (99%).

Size and persistence of aspen patches

Pre-harvest aspen patches in this study (n = 50) varied from 0.1 to 58.4 ha (Table 3). Size of aspen patches clearly influenced their probability of persistence or disappearance following clearcutting and 2 ha appears to represent a certain threshold. Aspen patches below this area had about a 50% probability of persisting following clearcutting whereas patches over this area had about a 4% chance of being extinguished (or a 96% chance of persisting) as a result of clearcutting (Fig. 4).

Table 3. Characteristics of persistent and extinguished aspen patches

	Persistent	Extinguished
Number of patches (%)	37 (74)	13 (26)
Size range (ha)	0.1-58.4	0.1-6.2
Mean size (ha)	7.8	1.6
Median size (ha)	2.7	0.7

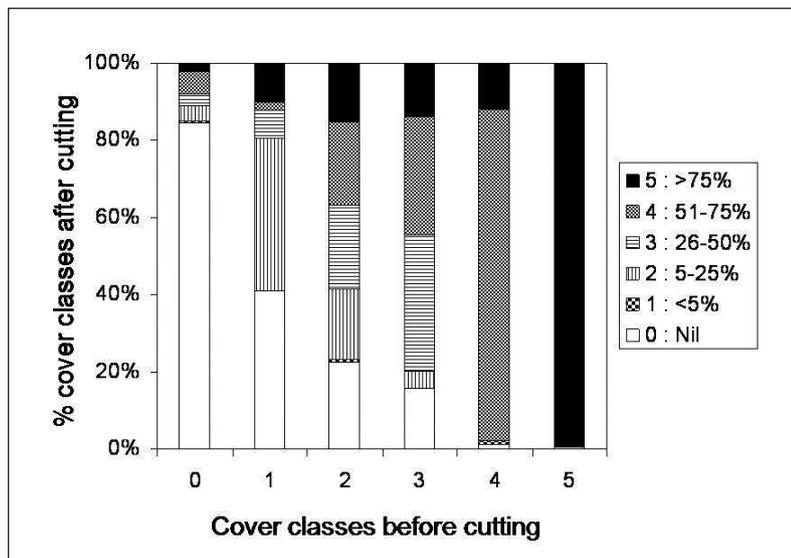


Fig. 2. Evolution of aspen patches, by initial cover class, following clearcutting (all sectors combined): before cutting versus after cutting. See Table 2 for cover classes.

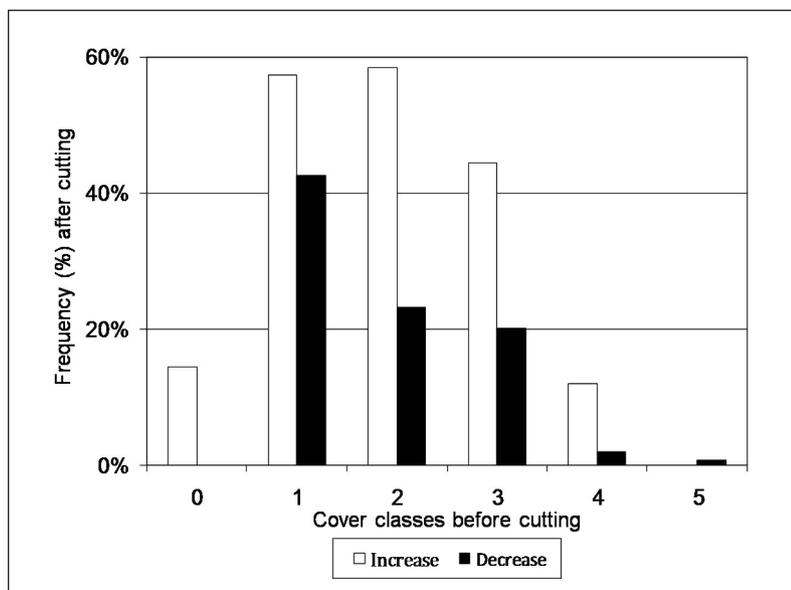


Fig. 3. Comparison of aspen cover class changes (increase or decrease) in aspen patches following clearcutting for all sectors combined: before cutting versus after cutting.

Probability of aspen colonization with distance from pre-harvest patches

The resolution of tracing patches on 1:15 000 and 1:20 000 aerial photos precludes us from drawing any conclusions concerning colonization in the first 20 m to 30 m from patches. However, analysis of the probability of colonization as a function of distance from patches, based on aspen presence in pixels in a 10 m × 10 m grid matrix, reveals that aspen recruitment cannot be attributed solely to suckering. In effect, while probability of colonization drops off sharply between 30 m and 60 m from aspen patches on most sites, a diminishing but still reasonable probability of establishment beyond this dis-

tance can be attributed to seeding. For example, the probability of colonization at 100 m ranges from 2% at the Casa site to 17% at the Dalet site (Fig. 5). Colonization on the outlier site, Rainboth, is likely the result of both strong internal sucker-origin and external (and unmapped) seed-origin colonization. (Three sites, Coigny 1, Laberge and Bacon, that had only small, low-cover aspen patches in pre-harvest stands, were excluded from this figure.)

Post-harvest regeneration inventory

Acknowledging that inventory transects were intentionally located to intersect sectors that had been photo-interpreted as post-harvest aspen patches, 28% of plots contained at least one aspen stem (Table 4). All plots were located on clay soils and plots containing aspen stems had a mean organic matter depth of 13 cm compared to 25 cm for plots without aspen and 34 cm for plots containing black spruce but no aspen. Of those plots containing at least one aspen stem, only 38% contained at least one black spruce stem and 57% had at least one softwood stem. In contrast, aspen stems were absent in 78% of plots containing at least one black spruce stem. Where both species were present (n = 694), aspen dominated by at least one height class in 30% of plots and black spruce was equal or taller than aspen in 70% of plots.

Discussion

Photo-interpretative analyses confirm our hypothesis that patches of trembling aspen embedded in black spruce stands situated on mesic clay soils tend to increase in density and in area following clearcutting. Moreover, original patch size and density both appear to influence patch dynamics—larger patches are more likely to persist following clearcutting and patches of aspen with cover values under 50% are the most volatile; that is, most likely to either increase or decrease in density. While probability of post-harvest colonization decreases sharply between 30 and 60 m from original patches, colonization from seeding appears to play a more important role in aspen expansion in the claybelt than previously thought. Aspen establishment from natural seeding is poorly documented in the literature although Landhäusser *et al.* (2010) report its occurrence on harvest-disturbed sites in the upper foothills region of west-central Alberta at elevations above the previous altitudinal limit of aspen. This altitudinal expansion is somewhat similar to the increase in the northern black spruce forest region in our study.

Density, size and persistence of aspen patches

Small aspen patches in the black spruce matrix may reflect a couple of situations. First, they could indicate a first or second

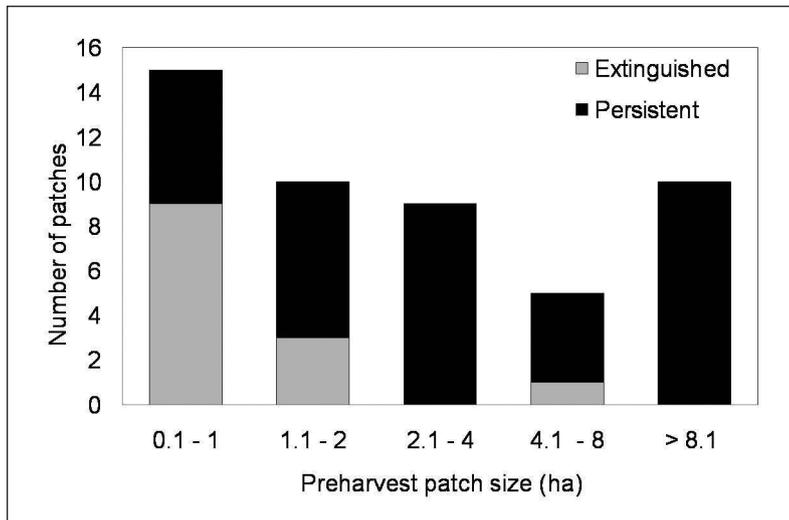


Fig. 4. Persistence–extinction outcomes following harvest of aspen patches as a function of patch area.

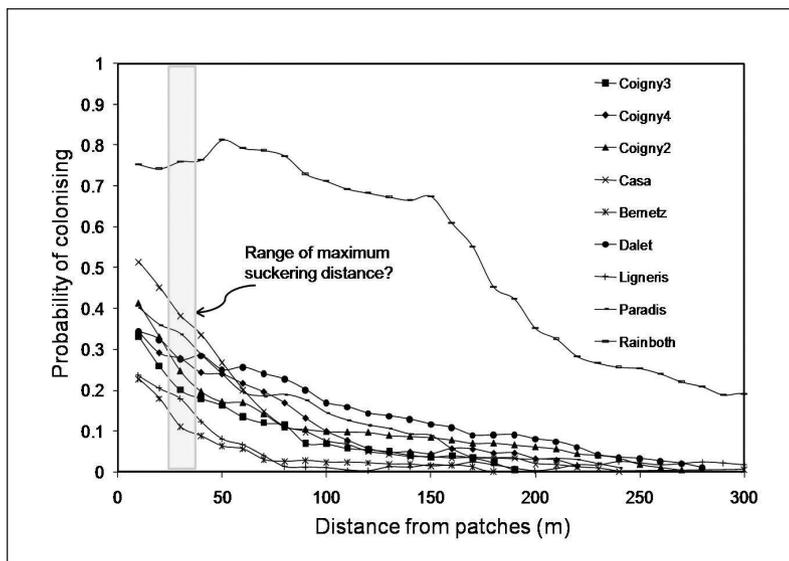


Fig. 5. Probability of colonization as a function of distance from patches. (Note: three sites that had only small patches of <5% aspen cover prior to harvest were not included in this analysis because colonization appeared to originate from external, unmapped sources.)

generation of mature, sucker-origin stems established around a single or small cluster of seedling-established stems that were killed in the fire that initiated the harvested stands. Second, small patches may actually be several generations older but contained by a surrounding, inhospitable rooting environment of thicker organic layers and colder soils that could effectively limit expansion. Under ideal conditions following disturbance, aspen situated within a patch probably tend to occupy a roughly circular zone of expansion around individual stems. Presumably, only physical barriers within the zone of influence of the rooting system restrict development. The form of aspen patches may therefore reflect limits to spatial expansion imposed by existing edaphic or other factors. Competition by conifer regeneration, broken topography (Comtois and Payette 1987), or soils that are too wet or too

cold (Frey *et al.* 2003, 2004) can all restrain expansion of aspen. The large size of certain aspen patches suggests that the physical environment has not restrained expansion in these cases. These large aspen patches can therefore exploit recurring disturbances of fire or harvesting, if they occur at relatively short intervals, in order to maintain themselves or even expand to neighbouring zones. In the absence of major disturbance, these large patches will likely fragment into smaller patches with lower cover values and eventually disappear. Senescence of the aspen component would lead to a progressive increase in conifer dominance with time (Greene and Johnson 1999, Bergeron 2000). At the other extreme, small aspen patches may be more vulnerable to their immediate environment. Following a fire or harvest, chances of survival of small patches are less (relative to large patches) if they are surrounded by conifer forest, unfavourable edaphic conditions (thick organic layer, poor drainage) or other physical barriers that limit suckering and seedling establishment.

Pure black spruce stands in this region appear to be relatively resistant to aspen invasion, probably because suckering cannot occur in the absence of a root source and because typically thick organic layers tend to impede seedling establishment (Zasada *et al.* 1977, Hogg and Lieffers 1991). Our field survey confirmed that aspen regeneration was largely limited to sites with organic layers half as thick as sites without aspen (mean of 13 cm vs. 25 cm). Depth of the organic layer may reflect soil moisture regime or time since (severe) fire (Lecomte *et al.* 2006) and whether a thick organic layer is the result of poor drainage or a long fire interval, both would be detrimental to aspen persistence.

Persistence of aspen following harvesting may also be partially attributable to the vigour of the root systems in place. Working in declining aspen stands in Alberta, DesRochers and Lieffers (2001a) observed live aspen root systems several years after parent trees had died. While underlining the benefits for suckers of being able to exploit an established access to soil resources, they also argued that because respiring roots can act as a carbohydrate sink, they probably require the higher photosynthetic capacity provided by relatively high densities of suckers to be maintained (DesRochers and Lieffers 2001b). We have no way of knowing if mature aspen in harvested stands were healthy or in decline, but this may partly explain why some patches persisted and others disappeared.

Colonization distances

Perhaps the most surprising result of this study concerns the distances to which aspen colonized following harvesting (Fig. 5). Typically, probability of colonization diminishes with

Table 4. Summary statistics from field inventory of post-harvest sectors

Total number of plots	1300
Mean organic matter thickness ^a of plots with aspen (std. dev.)	13 cm (16)
Mean organic matter thickness of plots w/o aspen (std. dev.)	25 cm (30)
Mean organic matter thickness of plots with black spruce and aspen (std. dev.)	17 cm (25)
Mean organic matter thickness of plots with black spruce w/o aspen (std. dev.)	34 cm (33)
Percentage of plots containing at least one aspen stem	28
Percentage of plots with aspen containing at least one black spruce stem	38
Percentage of plots with aspen without black spruce stems	62
Percentage of plots with aspen containing at least one softwood stem	57
Percentage of plots with aspen without softwood stems	43
Percentage of plots with black spruce without aspen stems	78
Relative heights for plots with at least one aspen and one spruce stem:	
% of plots with aspen > spruce	30
% of plots with spruce > aspen	42
% of plots with = height classes	28

^aOrganic matter depths >100 cm were noted as 100 cm.

distance from patches and suckering distances of 20 m to 30+ m from parent stems have been reported in the literature (Peterson and Peterson 1992, Shepperd 2001). While Namroud *et al.* (2005) measured maximal intergenerational clonal dimensions of 72 m and 104 m in mixedwood stands containing three cohorts of aspen, the delay of 11 to 18 years between the year of harvesting and the year of the post-harvest photos in our study was clearly insufficient to allow more than the initial wave of suckering from parent roots. This said, and given that clearcutting likely produced a certain quantity of suitable microsites for aspen establishment from seed, we conclude that seeding played an important role in aspen colonization, particularly in the surrounding environment of pre-harvest aspen patches. Although aspen regeneration by seeding has never been considered a reliable silvicultural technique, examples of seed-origin aspen colonization following natural disturbances have been reported. For example, Romme *et al.* (2005) observed extensive aspen regeneration from seeding following the Yellowstone fire of 1988.

Implications for Management

Our results suggest that intolerant hardwood encroachment will likely continue to occur in the black spruce forest of the claybelt under harvest regimes similar to clearcutting if soil conditions are favourable and if no silvicultural intervention is applied to counter this increase. (It is also worth noting that some aspen patches on several sites may have been influenced by road construction or disturbance around forest landings [see Fig. 1]). Silvicultural approaches, including the use of partial cutting or variable retention of mature aspen stems, may contribute to controlling hardwood expansion in the boreal forest. A certain increase in the proportion of intolerant hardwoods following harvesting could be acceptable if the silvicultural regime included, towards the end of the revolution, selectively harvesting hardwood stems to increase growth of residual conifer stems. Prévost and Pothier (2003) suggested that leaving at least 50% forest cover can limit aspen suckering as long as advance conifer regeneration is sufficiently dense and Ruel *et al.* (1998) stressed the importance of tall conifer regeneration in limiting the effect of hardwood competition on conifer growth.

This study confirms that forest harvesting as practised in the latter decades of the last century has had the effect of increasing aspen presence in the black spruce forest of the Quebec clay-belt. While the extent of this recent local expansion has been variable, depending on the size and density of previous aspen patches and site factors (Laquerre *et al.* 2009), it represents what could be the first wave of a more important forest cover transformation in the future. In effect, as this new landscape contains more aspen than 30 years ago, a longer-term transformation towards greater intolerant hard-

wood presence, possibly exacerbated by climate warming effects (Landhäusser *et al.* (2010), is very likely if corrective measures are not taken. This said, it should be noted that because aspen provides the largest-diameter trees in a landscape of relatively small-diameter forests, it constitutes a key habitat attribute for large cavity nesting species in the region (Drapeau *et al.* 2009); consequently, aspen control strategies should be tempered with considerations for biodiversity conservation.

Conclusion

While the scientific literature is rich with reports of intolerant hardwood expansion in boreal mixedwoods, this paper is one of the few that documents the phenomenon in the northern black spruce forest of the claybelt that spans northwestern Quebec and northeastern Ontario. Aerial photography is demonstrated as a useful tool for illustrating changes in forest composition through time but it is not without its limits. Because our results are based on interpretation of 1:15 000 and 1:20 000 aerial photos, there is the possibility that individual aspen stems were overlooked in pre-harvest photos or that other non-commercial hardwoods, notably speckled alder (*Alnus rugosa* [Du Roi] Spreng.) and willow (*Salix* spp.), were falsely identified as aspen in post-harvest photos. Indeed, while our post-harvest field survey revealed 28% aspen stocking, total stocking of all other intolerant and non-commercial hardwoods attained 78%, suggesting that competition by these species might pose a greater problem to black spruce seedling and sapling growth in this region than aspen. Nonetheless, it is worth mentioning that this photo-interpretive approach and time frame have been used elsewhere (MacIsaac *et al.* 2006) to study post-harvest gap formation in aspen-dominated stands. There is also a possibility that some cutovers were seeded in by aspen from surrounding areas that were not considered or mapped during pre-harvest interpretation, despite an effort to photo-interpret the periphery of all cutover sites. Intolerant hardwood expansion is clearly a management issue in the black spruce forest and implementation of both monitoring and adaptive management practices are required to measure changes in forest cover and develop appropriate silvicultural treatments.

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