Sugar maple (*Acer saccharum* Marsh.) growth is influenced by close conspecifics and skid trail proximity following selection harvest

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ABSTRACT

In this study, we quantified the effects of local neighbourhood competition, light availability, and proximity to skid trails on the growth of sugar maple (*Acer saccharum* Marsh.) trees following selection harvest. We hypothesized that growth would increase with decreasing competition and increasing light availability, but that proximity to skid trails would negatively affect growth. A total of 300 sugar maples were sampled ~10 years after selection harvesting in 18 stands in Témiscamingue (Québec, Canada). Detailed tree and skid trail maps were obtained in one 0.4 ha plot per stand. Square-root transformed radial growth data were fitted to a linear mixed model that included tree diameter, crown position, a neighbourhood competition index, light availability (estimated using the SORTIE light model), and distance to the nearest skid trail as explanatory variables. We considered various distance-dependent or -independent indices based on neighbourhood radii ranging from 6 to 12 m. The competition index that provided the best fit to the data was a distance-dependent index computed in a 6 m search radius, but a distance-independent version of the competition index provided an almost equivalent fit to data. Models corresponding to all combinations of main effects were fit to data using maximum likelihood, and weighted averages of parameter estimates were obtained using multimodel inference. All predictors had an influence on growth, with the exception of light. Radial growth decreased with increasing tree diameter, level of competition and proximity to skid trails, and varied among crown positions with trees in suppressed and intermediate positions having lower growth rates than codominants and dominants. Our results indicate that in selection managed stands, the radial growth of sugar maple trees depends on competition from close (≤6 m) conspecific neighbours, and is still affected by proximity to skid trails ~10 years after harvesting. Such results underscore the importance of minimizing the extent of skid trail networks by careful pre-harvest planning of trail layout. We also conclude that the impact of heterogeneity among individual-tree neighbourhoods, such as those resulting from alternative spatial patterns of harvest, can usefully be integrated into models of post-harvest tree growth.

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1. Introduction

Modelling the response of tree growth to partial harvesting in structurally complex forest stands presents a host of challenges (Peng, 2000; Puettmann et al., 2008a; Coates et al., 2009). In such stands, trees are of different size and age, and occupy various positions in the canopy. Moreover, partial harvest tends to maintain or favour heterogeneous conditions in terms of residual tree density (Grushecky and Fajvan, 1999), and light availability (Beaudet et al., 2002) and hence in neighbourhood competition. Therefore, an individual-tree approach should be favoured to model post-harvest growth response in such stands (Pretzsch, 1995).

Individual-tree growth models generally include as predictors a suite of tree characteristics such as tree size, vigour and/or crown position, as well as variables accounting for variation in competition levels experienced by individual trees. These variables can consist of stand-level characteristics such as residual stand basal area or density, or individual-tree competition indices. Among the latter, some are non-spatial in nature, in the sense that they do not aim at representing the competitive environment of a target tree in a spatially explicit neighbourhood, but rather as its relative situation in the stand (e.g., ratio between target-tree dimension and stand-level measures: Kiernan et al., 2008). Others can be considered spatially explicit in that they describe a target-tree neighbourhood within a given search radius and some indices

account for the distance to competing neighbours leading to distance-dependent indices (Stadt et al., 2007).

Obviously, the most appropriate approach to account for variation in competition level will depend on the ecological and silvicultural context. For instance, several studies found that distance-dependent competition indices did not perform better than distance-independent indices. However, most of such studies (according to Busing and Mailly, 2004; Stadt et al., 2007) were performed in stands where the spatial distribution of trees tended to be regular (e.g., plantations), and it has been argued that spatially explicit distance-dependent competition indices would be more likely to perform well in irregular stands where clustering of trees is common (Mailly et al., 2003; Busing and Mailly, 2004).

In recent years, increasing computer power and availability of light models have facilitated the use of computationally demanding light interception indices as an alternative or complement to conventional competition indices in growth models (e.g., MacFarlane et al., 2002; Mailly et al., 2003; Canham et al., 2004; Stadt and Lieffers, 2000; Astrup et al., 2008; Coates et al., 2009). However, mixed results have been reported regarding the usefulness of light indices compared to competition indices as predictors of tree growth. For instance, Mailly et al. (2003) found that indices computed from virtual hemispherical images did not yield better growth prediction than simpler distance-dependent competition indices. Similarly, Stadt et al. (2007) reported that the performance of the light indices was intermediate to poor when compared to conventional competition indices. Other investigators have explored the possibility of simultaneously using light and conventional competition indices as a way to partition competitive effects into below-ground (competition index) and above-ground (light interception) components. Such approaches allowed inferring on ecological processes such as competitive exclusion and species coexistence from growth rates (Canham et al., 2004; Coates et al., 2009).

While partial harvest modifies the competitive environment of residual trees, harvest operations have other effects that could enhance or diminish the possible benefits of reduced neighbourhood competition. During partial harvest, machinery traffic often leads to soil disturbance and compaction (Grigal, 2000), and residual trees near skid trails often suffer from root damage, as well as from impaired root development and water uptake (Startsev and McNabb, 2001; Nadezhdina et al., 2006; Komatsu et al., 2007). Such an impact is generally restricted to skid trails and areas nearby (Malo, 2008; Puettmann et al., 2008b; Roberts and Harrington, 2008). The stresses associated with skid trail disturbances are often reported to reduce stand productivity (Grigal, 2000), individual-tree growth, and survival (Murphy, 1983; Helms and Hipkin, 1986; Heninger et al., 2002; Puettmann et al., 2008b; Thorpe et al., 2008). However, most studies that have examined the effect of skid trails on tree growth and survival have focused on planted or natural regeneration (e.g., Murphy, 1983; Helms and Hipkin, 1986; Heninger et al., 2002; Puettmann et al., 2008b), while much fewer have evaluated the impact of skid trail proximity on residual mature tree growth and survival. Among the latter, equivocal results were obtained ranging from increased growth rates of trees located near skid trails (Roberts and Harrington, 2008), to absence of any effect (Hartmann and Messier, 2008; Hartmann et al., 2008), to a negative impact of skid trail proximity on residual tree survival (Thorpe et al., 2008).

In temperate northern hardwoods of the north-eastern United States and eastern Canada, uneven-aged sugar maple stands are a dominant forest component (Godman et al., 1990). The selection silvicultural system is widely used in such forests (Nyland, 1998; Bédard and Majcen, 2003) and involves the periodic removal of individual or small groups of trees across diameter and age classes at regular intervals. This silvicultural system seeks to maintain a specific diameter- and age-class distribution, to provide long-term consistency in yield, and to create or maintain favourable conditions for residual tree growth and regeneration (Smith et al., 1997; Nyland, 1998). While several recent studies examined the growth response of sugar maple following selection harvest (Jones and Thomas, 2004; Forget et al., 2007; Fortin et al., 2008; Kiernan et al., 2008), few included individual-tree competition indices, and none accounted for the possible influence of skid trail proximity on tree growth.

In this study, our main objective was to determine the effects of local neighbourhood competition, light availability, and the long-term effect of proximity to skid trails on sugar maple individual-tree growth following selection harvest. We hypothesized that growth would increase with decreasing competition and increasing light availability, but that proximity to skid trails would reduce growth. A secondary objective was to identify the attributes of the competitive neighbourhoods that have a significant impact on sugar maple growth through a comparison of several competition indices.

2. Methods

2.1. Study sites

The study sites were located approximately 60 km southeast of the city of Témiscaming (46°43′N, 79°04′W), Québec, Canada. The region is part of the western sugar maple-yellow birch bioclimatic domain, where the growing season is usually 170–180 days long. Mean annual temperature varies from 2.5 to 5.0 °C, and mean annual precipitation is 900 mm (snowfall ca. 25% of total) (Robitaille and Saucier, 1998).

In 2004 and 2005, 18 plots of 0.4 ha (50 m × 80 m) were established in uneven-aged northern hardwood stands that had been harvested by selection cuts in 1993 or 1994 (Table 1). All plots were located on level ground or on gentle slopes with good to moderate drainage, on ferro-humic podzols with underlying thin tills of glacial origin. The selection cuts aimed primarily at removing trees of low quality and vigour to increase overall post-harvest stand quality and reduce subsequent losses to mortality, as well as to maintain an uneven-aged structure in the residual stand. The pre-harvest BA ranged from 21 to 33 m^2/ha (28 m^2/ha on average), while post-harvest BA ranged from 14 to 24 m^2/ha (20 m^2/ha on average) (Table 1). The removal rate was ∼24% of stand basal area (BA) and was generally well distributed across diameter classes. Tree felling was done manually with chainsaws and whole trees were moved to forest roads with cable skidders. Skid trails were spaced approximately 15 m apart but spacing was not constant along the trail path. Thus, some areas were more affected by machinery traffic than others.

In the post-harvest stands, sugar maple (Ms) made up 74% of total BA, yellow birch (By, *Betula alleghaniensis* Britton) about 14%, American beech (Ba, *Fagus grandifolia* Ehrh.) roughly 4%, balsam fir (Fb, *Abies balsamea* [L.] P. Mill.) 3%, whereas white spruce (Sw, *Picea glauca* [Moench] Voss), red oak (Qr, *Quercus rubra* L.), red maple (Mr, *Acer rubrum* L.), eastern hemlock (He, *Tsuga canadensis* [L.] Carr.), and eastern white cedar (Cw, *Thuja occidentalis* L.) occurred in lower proportions (Table 1). Sugar maple stands in the study region have undergone several forest tent caterpillar (FTC, *Malacosoma disstria* Hubner) defoliations and the most recent ones occurred in 1986–1992, and in 1999–2002 (Hartmann and Messier, 2008).

2.2. Tree mapping

All live and standing dead trees ≥9.1 cm DBH (diameter at breast height, 1.3 m above ground), and all stumps were mapped in the 18 plots. To perform the mapping, a plot was divided lengthwise in two halves. The resulting center line served as the