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Modeling tree spatial distributions after partial harvesting in uneven-aged boreal forests using inhomogeneous point processes

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ABSTRACT

Old-growth forests are characterized by their compositional and structural complexity, which contributes to local biodiversity. To maintain these old-growth attributes in boreal forests, traditional even-aged management systems based on clear-cutting are gradually shifting to ecosystem-based management, which includes partial harvesting in uneven-aged stands. We investigated the spatial structure of trees within 31 plots that had been established in Canadian boreal forest after selection cutting. We used an approach based on heterogeneous point processes to investigate the relationship between tree density and distance to the nearest logging trail. Tree density was positively and log-linearly related with distance to logging trails, with large trees being particularly scarce near the trails. Using a statistical approach based on mixed models with random plot effects that accounted for distance to the nearest trail, we assessed how the spatial pattern of trees affected the diameter increment of trees. Seven-year diameter increments of trees with diameters <14 cm were negatively related to the distance to logging trails. Accordingly competitive interactions among trees left after partial harvesting, which aim at preserving old-growth forest attributes, were different from those of natural boreal forests. Based on these results, a stochastic model was applied using heterogeneous Gibbs point processes to realistically describe and simulate the location of residual trees after selection cutting in boreal stands that were represented by forest inventories without spatial information on tree location.

1. Introduction

In forest ecosystems, the spatial environment of trees is determined by various ecological processes that are driven by the characteristics of the soil, the climate, the topography, and disturbance regimes, among other properties (Bonan and Shugart, 1989). The resulting vegetation pattern partly governs the dynamics of tree development including competition, growth, mortality, and regeneration (Cale et al., 1989; Dieckmann et al., 2000). Analyzing these spatial patterns is therefore of major ecological interest, particularly with regard to the prediction and understanding of long-term forest dynamics.

In boreal forests, traditional forestry practices have been based on even-aged management, which is largely dominated by clear-cutting (Youngblood and Titus, 1996; Groot et al., 2005) that can hardly emulate partial mortality events that often occur in forests characterized by long-term stand-replacing disturbances (Bouchard and Pothier, 2011). However the increasing use of ecosystem-based management provides more room for uneven-aged partial cutting that is aimed at maintaining old-growth attributes (Seymour and Hunter, 1999; Pommerening and Murphy, 2004; Gauthier et al., 2008; Bergeron and Harper, 2009; Puettmann et al., 2009) such as irregular shelterwood systems (Raymond et al., 2009; Cimon-Morin et al., 2010). Hence there is an urgent need for accurate tools that can forecast the long-term dynamics of the resulting spatially and structurally complex stands. Indeed a variety of silvicultural treatments that have been rarely used, or which have never been previously employed (Haila, 1994; Groot et al., 2005), are now being considered for maintaining the presence of old-growth attributes in harvested stands. Since historical analogues (Groot and Horton, 1994) and long-term experiments (Mitchell and Vyse, 1999) of silvicultural treatments that result in structurally complex stands are rare, the modeling of stand dynamics has remained the preferred way in which the long-term effects of alternative management practices can be evaluated (Coates et al., 2003).

The use of individual-tree, spatially explicit models is recommended in modeling the dynamics of spatially and structurally complex stands (Weiskittel et al., 2011). These models characterize the growth of individual trees that compete for available resources with neighboring trees of various sizes. They are more flexible and can simulate more accurately partial cutting treatments such as thinning or irregular shelterwood systems. However this requires

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the knowledge of tree location, which is time-consuming and rarely available from common forest inventories. To overcome this problem simulation models can be calibrated with the spatial information that emerges from typical harvesting systems and, in turn, these models can be used to estimate the location of trees of known species and size from non-spatial inventories (Goreaud et al., 2004).

The reconstitution of the spatial dimension in forest inventory datasets is an active field of research (Batista and Maguire, 1998; Goreaud et al., 2004; Picard et al., 2009). Patterns of between-tree interactions relative to their size or species are studied to recreate realistic spatial distribution schemes. Such an approach has been used with natural forest areas, where between-tree competition largely explains the observed spatial distribution of trees. Consequently the literature related to modeling spatial tree patterns is almost exclusively dedicated to unmanaged forest plots (Pommerening and Stoyan, 2008; Grabarnik and Särkkä, 2009; Picard et al., 2009).

The spatial tree dynamics of naturally developed forest areas cannot be directly used to help predict post-harvest development of managed stands, especially those that have experienced partial cutting treatments. In these stands tree competition can be of minor importance locally since between-tree spacing has been manipulated by tending or harvesting operations. In this study, we hypothesized that recurrent spatial patterns of trees can be identified after partial harvesting in old-growth boreal forests, because harvesting machinery traffic imposes constraints that generates spatial inhomogeneity. Such a spatial pattern would affect the further growth of post-harvest trees, thereby emphasizing the link between spatial structure and stand dynamics. In line with previous studies that have used heterogeneous point processes to investigate the relationship between tree density and environmental spatial continuous fields such as altitude, topography or soil conditions (Waagepetersen, 2007; Law et al., 2009; Møller and Díaz-Avalos, 2010), we developed a realistic stand structure simulator for partially cut stands according to an inhomogeneous Gibbs point process model which took into account the spatial heterogeneity generated by logging trails.

2. Methods

2.1. Study area

This study took place in the southern portion of the northeastern Canadian boreal forest, in the province of Québec, Canada (Fig. 1). This area corresponds to the black spruce-feather moss bioclimatic domain, which is dominated by black spruce (*Picea mariana* (Mill.) BSP) and balsam fir (*Abies balsamea* (L.) Mill), with minor components of trembling aspen (*Populus tremuloides* Michx.), jack pine (*Pinus banksiana* Lamb.), and paper or white birch (*Betula papyrifera* Marsh.). For the period 1971–2000, the Bonnard weather station (50°44′N, 71°03′W; 506 m.a.s.l.) of Environment Canada, which is located in the center of the bioclimatic domain, indicates an average annual temperature of −1.8 °C and an average annual precipitation of 946 mm, with 33% falling as snow. The average growing season is 134 days, with an annual accumulation of 971 growing degree-days. Dominant surface deposits are glacial in origin, with deep tills, shallow tills, and fluvioglacial deposits. Soil texture is generally sandy with an abundance of stones and soil drainage is generally moderate.

2.2. Treatments and field measurements

Four 100 ha sectors were selected within the study area. These sectors had never been logged and were covered with old-growth irregular forests which are typical of the bioclimatic domain. Within each sector, five blocks of 20 ha were delineated, each of which corresponded to one of five treatments that had been applied in the summer of 2004: a control (no treatment); a commercial clear-cut, where all trees with a diameter at breast height (DBH, 1.3 m) that was greater than 9.0 cm were removed; a diameter-limit cut that removed all trees with DBH >14.0 cm; and two partial cuts that were aimed at conserving 50–60% of initial plot basal area. The present study focuses only on these two partial cut treatments, which correspond to a total 8 blocks (2 blocks × 4 sectors).

The partial cut treatments consisted of two versions of selection cutting, which is specifically designed to maintain the structure of irregular stands (Ruel et al., 2007). Trees that were to be harvested and skid trails were marked before harvesting. The level of harvesting in both selection cuts was around 45%, but the spatial pattern of harvest differed. "Selection cuts with permanent skidding trails" (SCperm) are characterized by permanent trails that are reused at each cutting cycle, while 5 m long secondary skid trails provided access to the whole plot for partial harvesting (Cimon-Morin et al., 2010). In the "selection cuts with temporary skidding trails" (SCtemp), logging trails were used at only one cutting cycle and only half of the area was treated, leaving untouched strips. To harvest the same wood volume as SCperm, tree removal was thus more intensive in the treated part in SCtemp. Detailed information regarding the characteristics of the treatments can be found in Ruel et al. (2007) and Cimon-Morin et al. (2010). Logging trails in both treatments were regularly spaced to help minimize machinery traffic. The distance separating two consecutive trails was prescribed to vary from 20 to 25 m. Immediately following the treatments, five 0.25 ha experimental units were established within each block that had been subjected to SCperm or SCtemp. Locations of the experimental units were randomly chosen. Permanent sample plots (400 m^2) were established at the center of each unit. This resulted in 40 permanent plots (5 units × 2 blocks × 4 sectors) that were distributed across the study area. Within each plot, individual trees with DBH >7.1 cm were numbered before recording their height (m), DBH (cm), species, and status (live or dead). Tree height was assessed with an ultrasonic hypsometer (Vertex IV, Haglöf, Sweden) and tree diameter was measured with a DBH tape. During the summer of 2010, tree locations within the plots were recorded by measuring the distance (d) and the azimuth (a) of each tree from the plot center. Polar coordinates (d, a) were converted to Cartesian coordinates (x, y) using trigonometric functions. Logging trails were spatially recorded by measuring their widths (edges were located by machinery tracks) and recording the spatial coordinates of three points located in the middle of the trail. Tree height, DBH and status were measured again during the summer of 2011. A minimum number of 10 trees per plot was required to reliably analyze the spatial structure of treated plots. Given this criterion, 31 partially cut plots were conserved for spatial structure analyses: 19 from the SCperm, and 12 from the SCtemp. The main characteristics of the plots are summarized in Table 1.

2.3. Statistical analyses

Statistical analyses were performed in R (R Development Core Team, 2011). The contributed package *Spatstat* (Baddeley and Turner, 2005) specifically supported spatial analyses. Mixed models were performed using the *nmle* package (Pinheiro et al., 2012).

2.3.1. Assessing the relationship between plot density and distance to the logging trail

2.3.1.1. Basic concepts about point processes and notations. For in depth descriptions of the theoretical background behind point processes and for technical definitions, an extensive literature exists on the theory of point processes (e.g. Cressie (1993), Stoyan and