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# The extent of edge effects increases during post-harvesting forest succession

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ABSTRACT

As human activities increase landscape fragmentation, edge effects on ecosystem properties are growing at an unprecedented rate. The influence of logging-induced edges on biodiversity can ultimately jeopardize the long-term sustainability of forest management practices. These effects are difficult to quantify, however, because temporal changes in edge influence on residual forests remain poorly understood. We examined vegetation gradients along 17 transects crossing the boundary between stands harvested 5–66 years ago and old-growth boreal forests. We estimated the magnitude and distance of edge influence (MEI and DEI, respectively) in uncut old-growth forests, and investigated how these attributes of edge influence changed during the regeneration of adjacent logged stands. Analyses indicated that three types of vegetation gradients were necessary to describe the temporal changes of edge influence on vegetation in uncut forests. No temporal changes were detected for MEI during 66 years of forest succession. Conversely, DEI in uncut forests ranged from 0 to 70 m, and increased as the adjacent logged stands regenerated. This edge expansion through time, together with persistent differences in vegetation between logged and old-growth forests for at least 66 years, raise questions as to whether or not forest management involving fast rotations between logging events can maintain biodiversity. In forest ecosystems where edge habitat widens while vegetation has still not recovered to its typical characteristics, the planning of an adequate combination of rotation time, size and perimeter/area ratio of residual forests becomes critical to achieve the objectives of sustainable management, including regional biodiversity preservation.

## 1. Introduction

Habitat loss and fragmentation that are induced by logging activities are major causes of biodiversity loss in forest ecosystems (Fahrig, 2003; Lindenmayer et al., 2006). Forest harvesting creates transition zones between harvested stands and unlogged forests, which can differ in structure and composition for several years. The effects of these forest edges are becoming increasingly important as the footprint of human activity increases in natural environments. Understanding the contribution of edges to ecological dynamics is therefore central to assessing the impacts of forestry on biodiversity.

Changes in vegetation and wildlife that are induced by the presence of edges have been intensively studied (Harper et al., 2005; Laurence et al., 2002; Lidicker, 1999; Murcia, 1995; Ries et al., 2004). The edge influence corresponds to the biotic and abiotic changes into the adjacent habitat, which can affect both logged stands and adjacent residual forests. Nevertheless, edge influence on residual forests motivates more interest because of its implication in biodiversity conservation (Harper et al., 2005; Murcia, 1995). After logging, microclimatic conditions at the edges of residual forests are different from their interiors. For example, higher levels of sunlight, higher wind speeds, and greater variation in humidity and temperature are found at the edge compared to the interior forest (Chen et al., 1995; Matlack, 1993). These differences can alter local ecological niches and, therefore, the abundance and diversity of organisms at the residual forest edge (Harper et al., 2005; Lidicker, 1999; Murcia, 1995). Old-growth forest specialist species that depend on habitat conditions found within the interior forest have been found to decrease in abundance at edges (Laurance et al., 2002; Niemelä et al., 2007; Pohl et al., 2007; Ries et al., 2004). Depending on the density of logging-induced edges and the extent of their effects, they may ultimately jeopardize the recovery of biodiversity.

Edge influence can be characterized by its magnitude (Magnitude of Edge Influence: MEI), i.e., the extent to which a measured parameter differs between the edge and the interior forest, and by its depth (Depth of Edge Influence: DEI), i.e., the distance from the limit of cutover into the adjacent forest over which there is a

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statistical difference in composition, structure, or function with the interior old-growth forest (Harper et al., 2005). DEI on vegetation is highly variable, ranging from a few meters to >100 m (e.g., Boudreault et al., 2008; Chen et al., 1992; Harper et al., 2004). This variability may be explained by the great number of processes and vegetation responses influencing edges, and differing over time among sites and ecosystems (see Harper et al., 2005, for a review). Harper et al. (2005) proposed a conceptual framework of expected primary and secondary responses by vegetation at the forest edges after their creation. Primary responses stem from the direct effects that occur during the creation of edges (e.g., machinery, microclimate effects), resulting in possible damage or death of trees. The net outcome is a loss in canopy cover and an increase in downed wood at the forest edge compared to the forest interior (e.g., Harper and Macdonald, 2002; Harper et al., 2004). Secondary responses consist of changes in the structure and composition of understory and ground vegetation (e.g., increasing sapling density and understory cover) arising from primary responses affecting the original abiotic and biotic conditions at the edge (Harper et al., 2005). Over time, as logged stands adjacent to old-growth forest regenerate, the edge may become less sharp and MEI can decrease. Conversely, edge influence may expand over time due to, for example, persistent winds felling stems, snags, and trees, and opening the canopy (Chen et al., 1992; Harper and Macdonald, 2002; Laurance and Curran, 2008). Few studies have focused on the temporal dynamics of cut edges, and results are usually limited to the first 25 years after edge creation (e.g., Harper and Macdonald, 2002; Rheault et al., 2003). However, Matlack (1993, 1994) showed that edge vegetation can still be different from the interior forest 63 years after edge creation. Even so, long-term vegetation responses and edge temporal dynamics (softening or expansion) remain poorly documented. Contrary to softening, expanding edge effects over time should amplify the negative impacts of edges on both plant and animal species inhabiting old-growth forests, and these effects can therefore be an impediment to achieving sustainable forest management. Knowledge of the complex, long-term impacts of logging-induced edges on vegetation can enhance our capacity to alleviate the consequences of forestry practices on ecosystem dynamics by proposing appropriate forest management guidelines.

Our study took place in Northeastern Canada, in a boreal landscape that is dominated by old-growth forests where the fire cycle exceeds 250 years (Bouchard et al., 2008) and where logging (predominately clearcutting with <10% tree retention) has been an important disturbance agent for the past 50 years. Our aim was to (i) identify edge boundaries, (ii) estimate MEI and DEI in adjacent unharvested old-growth forests (>120-years-old), and (iii) determine how the vegetation structure in the old-growth forest edges, and DEI and MEI change during the first 66 years that the adjacent logged stands regenerate. To our knowledge, this study is the first to assess the long term dynamics of logging-induced edge influence at regenerating forest edges.

## 2. Materials and methods

### 2.1. Study area

The study was conducted in the boreal forest of Northeastern Quebec, Canada (51°02′12″N, 69°11′41″W; Fig. 1). Annual precipitation ranges from 1000 to 1400 mm, and annual mean temperature varies from −2.5 to 0.0 °C (Boucher et al., 2006). The study area is situated in the eastern black spruce–moss bioclimatic region and is characterized by long fire cycles which produce uneven forest stands shaped by blowdown and senescence (Bergeron and Fenton, 2012; Bouchard et al., 2008). The forest landscape is composed of 70% irregularly structured late-successional stands dominated by black spruce (*Picea mariana* (Miller) BSP), or a combination of black spruce, balsam fir (*Abies balsamea* (L.) Miller), and white or paper birch (*Betula papyrifera* Marshall) (Boucher et al., 2003). The ground is mainly covered by feather moss (*Pleurozium schreberi* (Brid.) Mitten) in mesic areas, and *Sphagnum* spp. in poorly drained areas.

### 2.2. Experimental design

We surveyed 17 paired habitats during summer 2011 that included a logged stand adjacent to unharvested old-growth forest (Fig. 1). Each habitat (logged stand versus old-growth forest) covered an area of at least 200 × 250 m, and shared a boundary with the adjacent habitat of at least 250 m. To evaluate how the influence of logging-induced edge varies with natural regeneration of logged stands, we used a chronosequence approach (Cole and van Miegroet, 1989). This method assumes that all study sites are similar (e.g. in terms of pre- and post-logging ecological conditions and logging treatments), with the exception of time since logging. We selected pairs of cut (5–66 years; Appendix A) and uncut stands according to three criteria: (1) stand structure and composition within the old-growth forest were relatively similar among sites, (2) conifers (black spruce and balsam fir) dominated the regenerating stands; and (3) streams and roads were absent in both habitats. Edge orientation can be an important determinant of edge influence (Burton, 2002; Hylander, 2005). We did not control for this effect in the analysis (Appendix A), but we ensured that edge influence did not covary with edge orientation.

### 2.3. Characterization of vegetation

Vegetation was characterized within each paired habitat along one 300 m transect placed perpendicularly with, and centered on the limit of the cutover. The transect extended 150 m into each habitat (Fig. 1), and was comprised of 31 stations, which were set 10 m apart. We characterized each station by measuring vegetation structure associated with 3 height strata: ground cover, understory cover, and overstory cover. We focused on vegetation structure, because it is a recognized factor controlling edge influence in black spruce boreal forests (Harper et al., 2003, 2005; Bergeron and Fenton, 2012). Ground cover (in percent) of bare soil, rocks, sand, water, moss, *Sphagnum* spp., epigeic lichens, herb species (e.g., *Carex* spp., *Cornus canadensis* L.), low shrubs (<20 cm height; *Salix* spp., *Gaultheria hispidula* (L.) Muhl. ex Bigelow), high ericaceous species (>20 cm height; *Rhododendron groenlandicum* (Oeder) Kronn & Judd, *Kalmia angustifolia* L., *Vaccinium* spp.), fallen branches, dead leaves on the ground (from deciduous trees, *Kalmia* and *Rhododendron*) and fungi were visually estimated within two 1 × 1 m quadrats that were randomly located 2 m away from the side of the station. Coarse woody debris volume (CWD, $m^3$ per hectare; length $\geqslant$ 1 m and diameter at both ends > 9 cm), which is a measure of near-ground structure, was estimated for each station using line-intercept sampling (Ståhl, 1997) along two perpendicular 6 m transects that were randomly oriented and centered on the station. The diameter of each piece of CWD was recorded at the intersection of the line transect. CWD volume was calculated using the following equation (de Vries, 1973): CWD volume = $\pi^2/8L \times \sum(d^2)$, where $L$ is the transect length (cm), and $d$ is diameter of the coarse woody debris (cm). Understory cover was estimated by counting all seedlings (i.e., <1.30 m height) and saplings (i.e., $\leqslant$9 cm dbh and $\geqslant$1.30 m height) and measuring the diameter at breast height (dbh, 1.3 m) of all saplings in one 2 × 2 m quadrat centered on the station. Overstory was characterized by recording tree species, and counting and measuring the dbh of all live trees and snags (i.e., >9 cm dbh) within the 2 × 2 m quadrats.