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Temporal dynamics and causes of postharvest mortality in a selection-managed tolerant hardwood forest

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ABSTRACT

Tree mortality following partial harvesting may significantly affect tree community dynamics, timber supply, and wildlife habitat in managed forests. However, the rates, causes, and consequences of postharvest mortality (PHM) have rarely been investigated in commonly used silvicultural systems. We applied a chronosequence approach combined with tree-ring-based dating of mortality events to investigate PHM following single-tree selection silviculture in a hardwood forest in central Ontario, Canada. Observed rates of PHM were best described by a negative exponential model, with an initial peak of 0.78–0.94% year^{-1} occurring within the first two years postharvest, and decreasing to ~0.55% year^{-1} three through five years postharvest. At six through 10 years postharvest, observed tree mortality was stable at ~0.21% year^{-1}: these rates were considerably lower than those observed in unmanaged stands at the same site (0.96% year^{-1}). Trees $\leqslant$17 cm in diameter were most susceptible to PHM, as were two softwood species (*Picea glauca* (Moench) Voss and *Abies balsamea* (L.) Mill.) and *Betula alleghaniensis* Brit. *Acer saccharum* Marsh. and *Fagus grandifolia* Ehrh. were least susceptible. Causes and types of mortality changed significantly with time after harvest: initially, mechanical damage from skidding and felling resulted in most dead trees observed as downed wood. With time, biotic agents (fungal infections, senescence) became more prevalent agents of mortality, increasing the proportions of standing dead trees. Our results indicate that PHM rates following selection harvesting are small compared to those following other retention harvest systems, but in the long term disproportionate effects on certain species are likely to affect the structure and function of managed northern hardwood forests.

1. Introduction

In much of the northern hardwood forest region of North America, selection silviculture is a common forest management system and it is progressively becoming a more common forest management practice globally. In single-tree selection harvests in eastern North America, roughly 30% of standing basal area is removed from the stand and residual trees are retained across a full range of size classes approximating a target tree diameter distribution, intended to ensure recruitment of trees into successively larger size classes (Nyland, 1998). Also retained are other critical habitat features such as large live trees, a continuous canopy with multi-layered vegetation, substantial coarse woody debris, and both cavity and mast trees (Coates and Burton, 1997; OMNR, 1998; Franklin et al., 2002). Since a relatively small proportion of trees are removed in a given stand entry, selection silviculture is often considered more ecologically benign than other silvicultural systems (Caspersen, 2006).

With single-tree selection harvesting, a large proportion of the residual trees are exposed to possible mechanical damage during felling and skidding operations (Lamson et al., 1985; Ostrofsky et al., 1986; Cline et al., 1991; Anderson, 1994; Nichols et al., 1994). While damage following selection harvests has been well documented, understanding and quantifying how the damage may affect stand structure and dynamics remains largely speculative (e.g. Moore et al., 2002). A few studies have evaluated how harvest-related damage influences residual wood quality and/or postharvest growth rates (Nyland et al., 1977; Cline et al., 1991; Hartmann et al., 2008; Jones et al., 2009). By comparison, the effects of selection harvests on postharvest tree mortality (PHM) have not been well documented.

Following partial or structural retention harvests (*sensu* Groot et al., 2005), the rate of PHM has been suggested as one of several possible means to objectively assess the success or failure of silvicultural treatments. For example, based on an informal survey of British Columbian foresters, Coates (1997) suggested residual tree mortality rates >10% would be sufficient to deem a silvicultural treatment a “failure”. From a timber management perspective, elevated PHM can drastically influence timber supply projections,

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and has been shown to strongly affect stand structure and long-term dynamics, at least in boreal forests (e.g. Thorpe et al., 2010). From an ecological perspective, the effects of elevated PHM rates in managed hardwood forests are less clear. Some authors have suggested higher tree mortality may be beneficial as it creates high-value wildlife habitat in the form of coarse woody debris (Thorpe and Thomas, 2007; Vanderwel et al., 2008, 2010); others have found that selection harvests can either reduce or increase the amount of wildlife habitat such as standing dead trees (snags) and live cavity trees (Holloway et al., 2007; Kenefic and Nyland, 2007; Bladon et al., 2008; Cimon-Morin et al., 2010). Quantifying PHM is thus critical both from ecological and management perspectives to evaluate how silvicultural treatments influence forest structure and function.

To date most research on PHM in North America has been concentrated in boreal or western conifer forests, where retention rates are much lower than those following selection harvests (reviewed by Thorpe and Thomas, 2007; Bladon et al., 2008; Thorpe et al., 2008; Cimon-Morin et al., 2010; Spence and MacLean, 2011; Solarik et al., 2012). These studies indicate that postharvest mortality rates are highly variable, ranging between very small increases of <2% (e.g. Coates, 1997; Deal et al., 2002) to considerable increases of over 75% (Ruel et al., 2001). By comparison, few published studies have quantified mortality rates after single-tree selection harvesting. Caspersen (2006) found that, compared to background mortality rates (1.5% year^{-1}), tree felling increased tree mortality by 0.2–3.3%; these elevated levels returned to background rates within 6–8 years after harvesting. However, Caspersen (2006) examined experimental stands where trees were felled, but skidders did not remove timber. Thus, increases in PHM in operational stands are likely higher given that skidders are often the primary agents of residual tree damage and mortality during harvesting operations in a variety of managed forests (Lamson et al., 1985; Nichols et al., 1994; Thorpe et al., 2008). Published data from commercial selection-managed forests in Quebec offer mixed support for higher rates of PHM: assuming natural mortality rates of 1.5% year^{-1}, data extrapolated from Forget et al. (2007) suggested mortality increases of 0.4% over 10 years, while others have reported increases in mortality of 10.5–12.2% over 10 years (Bédard and Brassard, 2002).

Information on the causes of PHM mortality following selection harvests is even more limited. Previous work from other forest types and harvesting regimes has focused on windthrow as a main postharvest mortality agent (Ruel, 1995; Coates, 1997; Huggard et al., 1999; Ruel et al., 2001, 2003). Yet selection harvests, with their low removal rates, may result in different causes of mortality and these may change through time. Trees showing severe damage from felling and skidding operations are likely to die very quickly. In contrast, if harvesting does not kill trees immediately, those exposed to skidder activity and felling damage may be predisposed to higher long-term mortality risk due to fungal infections (Hesterberg and Ohman, 1963; Nichols et al., 1994; Mycroft, 2010) or reduced competitive status (Jones and Thomas, 2004; Bladon et al., 2008; Hartmann et al., 2009). Differences in causes of mortality could also lead to differences in the type and function of coarse wood (i.e., standing vs. downed) present on the landscape (Bladon et al., 2008), with implications for the availability of wildlife habitat (Holloway et al., 2007; Vanderwel et al., 2008, 2010).

This study was designed to elucidate patterns and causes of tree mortality following single-tree selection harvesting in Ontario's hardwood forests. We addressed three main questions: (1) What are the temporal patterns of postharvest tree mortality following selection harvesting? (2) What tree species and size classes are most susceptible to mortality following single-tree selection harvesting? and (3) What are the main types and causes of tree mortality following selection harvesting?

2. Methods

2.1. Field-based study

Field sampling was conducted at the Haliburton Forest and Wildlife Reserve (HF), a 25,000-ha privately owned forest in central Ontario, Canada (43° 13′ N, 78° 35′ W). Located within the Great Lakes-St. Lawrence forest region, the forest has been managed by selection harvesting for the past 40 years. Prior to this time, the forest was high-graded for *Pinus strobus* L. and *Betula alleghaniensis* Brit. (Mrosek et al., 2006). *Acer saccharum* Marsh. is the dominant species in the forest, comprising roughly 60% of the total basal area which ranges between $\sim$ 15-30 m^2 ha^{-1} on most upland sites (Domke et al., 2007). Other commercial hardwood species include: *Fagus grandifolia* Ehrh., *B. alleghaniensis*, *Prunus serotina* Ehrh., *Fraxinus americana* L., and *Quercus rubra* L. (Jones and Thomas, 2004).

Selection management in HF removes approximately 1/3 of the standing basal area every 20-25 years. All harvested blocks in the study were cut using conventional harvesting techniques common in the region (OMNR, 1998). Specifically, harvesting is designed to approximate a target size class distribution (q-ratio of 1.16), with trees directionally hand felled, topped, and delimbed using chainsaws. Tree-lengths were dragged up to 1 km to small landings with cable skidders. Because the silvicultural objective of the selection harvesting is to naturally regenerate shade-tolerant and certain mid-tolerant hardwoods (i.e. *B. alleghaniensis*, *P. serotina*, and *Q. rubra*), no deliberate understorey vegetation management or soil scarification prior to or immediately post harvest was done in any of the blocks. The layout of skid trails was typical of selection harvesting with main skid trails, approximately 3-5 m wide, spaced every 25-50 m depending on local topography. Secondary and tertiary trails were located as needed to access trees marked for removal.

Since 1985, accurate records of cutblock locations have been maintained throughout HF making it possible to examine PHM using a chronosequence approach. Our study made use of a subset of sample plots established as part of a previous study designed to analyze postharvest tree growth and gap-closure rates (see Domke et al., 2007; Jones et al., 2009). Operational stands from seven harvest years were identified, spanning an 11-year chronosequence (Table 1). For each harvest year (except 2000), two to three distinct cutblocks were identified and located to ensure spatial interspersion of plots within a given harvest year. In all cutblocks, harvesting occurred during the summer, fall, and winter months. Removal rates in sampled plots ranged from 7.3-15.5 m^2 ha^{-1} of the standing basal area (Domke et al., 2007). Within each cutblock, primary skid trails were located and transects extending the length of the skid trail were established. At 100-m intervals along the main transect, paired 20-m fixed radius plots were established with plot center points located at a 50 m perpendicular distance from transect lines. Although we attempted to resurvey all plots, we could not relocate five plots harvested in 1997, and one plot harvested in 1998 (Table 1). In total 134 inventory plots were surveyed, representing a 16.84 ha area of forest. All cutblocks harvested during or prior to 2003 were sampled June through August 2005, while cutblocks harvested in 2005 were sampled in August 2006.

Within each plot, all live trees $\geqslant$8 cm in diameter at 1.3 m aboveground (dbh) and cut stumps had been previously identified to species, measured, and mapped (Domke et al., 2007; Jones et al., 2009). Upon revisiting these plots, we located and identified all dead trees that were not intentionally felled (identified by the lack of a cut surface), measured diameter at 1.3 m from the base, and assigned a decay class category (consistent with Vanderwel et al., 2008). A detailed diagnostic examination of physical characteristics was then conducted to infer the main cause of mortality. Infer-