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Factors driving tree mortality in retained forest fragments

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ABSTRACT

Green tree retention is often applied in forests otherwise harvested by clearcutting. Its aim is to support biodiversity by contributing to a continuity of living trees and large-diameter dead wood in the new generation of a forest. However, high levels of mortality can undermine the aims of tree retention and pose a concern for forest managers. Therefore, knowledge about the mortality of retention trees over the long term is needed. We calculated cumulative tree mortality for the seven most common tree species up to 20 years after clearcutting based on a chronosequence of dead and living trees in 583 tree groups on 206 clearcuts distributed over a wide area in boreal central Sweden. For all tree taxa combined and for the three most common tree taxa (Scots pine, Norway spruce and two birch species) we modeled tree mortality based on structural and environmental variables measured for each tree group and characteristics of the clearcut using generalized linear mixed effects models. The cumulative mortality averaged over all clearcut ages was 12% for Scots pine, 25% for Norway spruce and 16% for birch. Only 10% of all retention tree groups had a mortality >50%. Key factors reducing mortality for all tree taxa combined were tree density, tree volume of a retention group and the position at a former stand edge abutting open habitat, while a high wind exposure increased tree mortality. For the three most common species (pine, spruce, birch), the same factors as for all taxa combined were of importance, except tree density that resulted in species specific responses. For pine and spruce, the presence of seed trees on the clearcut reduced mortality. Increased mortality was additionally observed on wet soils. Mortality increased with tree height in birch and with diameter and slenderness ratio in spruce. Generally, a focus on retaining trees in groups with large tree volumes and tree density in less wind exposed positions and on forest edges will decrease the mortality after clearcutting and thus also reduce dead wood input.

1. Introduction

Retaining living trees at harvesting ("green tree retention") is a conservation practice that has been integrated into production forestry with the aim of promoting biodiversity. Retention forestry can be perceived as an emulation of natural moderate-impact disturbances like fires, insect outbreaks, and storms. Consequently, a heterogeneous mosaic of structures of dead, dying and living trees remains (Hunter, 1993), and thus differs from the traditional clearcutting forestry, where virtually all forest structures are removed (Lavoie et al., 2012). Retention forestry was first introduced in North America about 25 years ago, and has since then been increasingly and widely applied in various boreal, temperate and subtropical forests worldwide (Gustafsson et al., 2012). Tree retention has been found to promote early successional species dependent on living or dead trees (Vanderwel et al., 2007), to preserve species from the previous forest stand on the clearcut (Tittler et al., 2001; Hylander et al., 2004; Rosenvald and Lõhmus, 2008; Hautala et al., 2011; Hylander and Weibull, 2012; Fedrowitz et al., 2014; Rudolphi et al., 2014), to increase the structural diversity (Hunter and Bond, 2001; Rosenvald and Lõhmus, 2008), to enhance landscape connectivity (Chan-McLeod and Moy, 2007), to secure ecosystem functions like herbivory (den Herder et al., 2009), mycorrhizal processes (Cline et al., 2007), or nutrient retention (Pastur et al., 2013), and to improve the visual appearance of the harvested area (Ribe, 2006, 2013; Ford et al., 2009).

For realizing all positive effects for biodiversity, a large proportion of the retained trees have to survive the substantial changes in the post-harvest environment to ensure a gradual long-term input of deadwood as well as a continuous presence of living trees (Work et al., 2010). Initial mortality after clearcutting has indeed been regularly found to be enhanced (Scott and Mitchell, 2005). Due to storms, almost all trees in small retention groups may be wind-felled (Esseen, 1994). Even without a storm in the first year

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after cutting, the 5–10 year mortality rates can range between 20% and 50% (Solarik et al., 2012). As a comparison, the annual mortality rate in natural boreal forests does usually not exceed 1% (Franklin et al., 1987; Hytteborn et al., 1991; Jonsson and Dynesius, 1993; Linder, 1998). If trees survive a first period of increased mortality, they can however often adapt to the more exposed growing conditions by reshaping their canopies (Foster, 1988), and strengthening their root-system and diameter growth (Holgen et al., 2003; Peterson, 2004), resulting in lower long-term (>5 yr) mortality rates (Jönsson et al., 2007). Thus, to ensure a successful application of tree retention, knowledge about how to limit the mortality of retention trees is essential. Mortality in retention trees often differs between tree species due to their different vulnerability to changes in growing conditions after harvesting (Valinger and Fridman, 1999). Factors influencing long-term (>5 yr) retention tree mortality have only rarely been studied (Steventon, 2011).

Mortality has been found to increase in retention tree groups with increasing tree height (Lavoie et al., 2012), tree slenderness (tree height/tree diameter) (Scott and Mitchell, 2005), age of the retention group (Hautala and Vanha-Majamaa, 2006) and exposure to wind (Rosenvald et al., 2008). Furthermore, mortality has been found to decrease in retention tree groups with increasing tree density (Steventon, 2011), area of the retention tree group (Jönsson et al., 2007; Steventon, 2011), and in retention groups at former stand edges abutting open habitats (Rosenvald et al., 2008). So far, long-term studies on tree mortality have relied on only a few observed retention tree groups (Esseen, 1994; Jönsson et al., 2007) while group-retention studies with more samples (Hautala and Vanha-Majamaa, 2006; Lavoie et al., 2012) have included only observations of a few years of post-cut mortality (1–5 years). Therefore, recommendations for retention forestry management have often been more based on foresters' practical experiences than on analyses of tree mortality patterns. The present study overcomes these limitations by calculating the levels of tree mortality for seven tree species up to 20 years after clearcutting for a large number of retention groups, and by investigating how overall mortality accumulates over time.

We sum up living and dead trees for all seven surveyed tree species and model the probability of tree mortality based on a wide array of structural and environmental characteristics of the respective tree group and clearcut in order to give general advice to foresters. We then repeated the procedure for the three most common species – Scots pine, Norway spruce and birch to identify species specific responses to mortality factors. Thereby, we answer the following questions: How does tree mortality change over time? Does tree mortality differ between species? Which factors influence tree mortality most?

2. Methods

2.1. Study region

Our study was conducted in the southern boreal forest region in central Sweden. Surveyed clearcuts were spread over an area of about 100,000 km^2 (Fig. 1). Mean temperatures in the area in January range from −14 °C to −10 °C. In the warmest month, July, mean temperatures range from 16 °C to 18 °C (1960–91). Precipitation is about 600–800 mm a year (1960–91) (Wastenson, 1995). In our study area, forests are usually even-aged and of clearcut origin and consist of about 40% of Norway spruce (*Picea abies* L.), 40% of Scots pine (*Pinus sylvestris* L.) and 11% of birch (*Betula pendula* Roth. and *B. pubescens* Ehrh. (Cory and Nilsson, 2009). The remaining smaller percentages are broadleaved trees, mainly European aspen (*Populus tremula* L.), rowan (Sorbus aucuparia L.), goat willow (*Salix caprea* L.), black alder (*Alnus glutinosa* L.), gray alder (*A. incana* L.), and the conifer European larch (*Larix decidua* Mill.).

2.2. Study sites

We selected 206 clearcuts that were cut between 1 and 20 years ago and with at least two (preferably three) retention groups with clearly different characteristics. They were randomly selected from clearcuts with retention groups inspected after harvesting (in a database called "grönt bokslut" in Swedish) provided by the managing forest company (Stora Enso AB). The age distribution was skewed toward younger clearcuts (Fig. A.1), because there were fewer inspections of retention groups after harvesting in the early years of retention forestry.

The company had surveyed all the studied clearcuts 2–6 months after the cutting. The data we obtained included detailed maps. Additionally, the soil and vegetation type of each retention group was briefly described. The average area of the clearcuts was 16.5 ha (±7.6 SD) and the rotation period in the area has been typically about 80–100 years. The forest company's data was mainly used to select the studied retention groups within each clearcut: on each clearcut, we chose three (in a few cases two) retention groups representing the variation in exposure, moisture and size of the retention groups on each clearcut, resulting in a total of 581 tree groups surveyed. In 59% of those retention groups, pine was the most numerous tree species, in 25% retention groups it was spruce and in another 13% of retention groups it was birch, while 4% of all retention tree groups had equal amounts of pine and spruce. On average, 23 (±20 SD) trees per retention group were retained, amounting to a total of 13,273 retained trees. 53.1% of these trees were Scots pine, 27.3% Norway spruce and 14.3% birch trees. Alder, aspen, willow and rowan contributed together with less than 6%.

2.3. Tree mortality

Mortality was assessed from field observations made in retention groups in 2012 and 2013: we counted all living and dead trees, only including those dead trees that were judged to have been living at the time of clearcutting. The mortality of each tree species was calculated as percentage of dead trees to the sum of living and dead trees of that species.

Beside wind-related mortality, competition, unfavourable weather conditions, attacks by pest species and harvesting damages may contribute to retention tree death. We collected data on beetle occurrence on the trees by looking for larvae, larval feeding patterns and fully grown beetles (imagoes) and found beetle traces on only 161 trees. However, only a small number of those (less than one third) were beetles that are able to cause damages on living trees. No major outbreak of any tree-killing bark beetle has occurred in our study area within the last 20 years according to the forest company managing our study sites, meaning that beetle-induced tree mortality should not be expected to play a major role for our study.

We differentiated trees that had died recently from trees that had died before the cutting by visually estimating the degree of wood decomposition (cf. Steventon, 2011). Especially in older sites, there may have been uncertainties in these estimations. However, typically, the study sites had been managed with thinnings before harvesting, and therefore dead trees were rare in the mature forests before harvesting. Dead trees may have been removed, but tree removal is illegal according to Swedish law for private people and most of the study sites are situated in sparsely populated areas. Therefore we believe this issue to have negligible influence on the outcome of our study. We noticed ten cases, where retention trees had been apparently cut after logging, presumably