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The effects of a large-scale ice storm event on the drivers of bark beetle outbreaks and associated management practices

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ABSTRACT

Large-scale disturbances in forests are becoming more frequent due to a changing climate. Biotic disturbances can have cascading effects and therefore have a significant economic impact in forestry. It is therefore important to gain an understanding of the drivers of forest pest outbreaks in epidemic situations after large-scale disturbances and the implications for forest management. We investigated the influence of drivers on the bark beetle outbreaks following a large-scale ice storm in 2014 in Slovenia. A country-wide survey was done on the variables affecting ice storm damage to spruce trees. Additionally, the influence of the drivers of bark beetle attacks on outbreak intensity was assessed and compared under epidemic and endemic situations, and the effectiveness of forest management measures was assessed. Spruce trees were either uprooted or snapped, or the crown was lightly to severely damaged. The outbreaks under endemic situations were potentiated by the increasing amount of spruce and reduced by increasing slope. After the ice storm, the amount of sanitary felling because of outbreaks increased in areas with more steeper slopes, where the ice storm took place. An increase in the level of disturbance and a higher availability of dead and weakened trees positively affected bark beetle populations. The removal of dead trees alone in the first year after the ice storm was found to be an insufficient measure for preventing bark beetle outbreaks. The ineffectiveness of current practices suggests that bark beetle management should be reconsidered with regard to large-scale disturbances. When defining measures against bark beetle outbreaks, drivers in epidemic situations should be prioritized over those that are important in endemic situations. The results imply that the known factors that affect bark beetle attacks are not necessarily the same as those that drive bark beetle attacks after extraordinary disturbance events. Mixed stands should be promoted in forests for sustainable management.

1. Introduction

Large disturbance events have been taking place for centuries and are thought to be one of the main drivers of forest structure and composition (Angelstam & Kuuluvainen, 2004; Fischer et al., 2013). In the last century forests have faced the additional threat of a changing climate, which has increased the probability of large disturbance events such as wind throw, snow and ice storms (Schelhaas et al., 2003). Such large disturbance events are expected to increase in the future (Seidl et al., 2014). Many of these events are abiotic events, and secondary biotic factors such as diseases and insects can also have a large impact on forests. In most cases a cascade takes place in which abiotic disturbances are followed by insect outbreaks (Kausrud et al., 2012). It is therefore essential to understand the processes following disturbance events in order to improve future forest management, particularly given that large-scale disturbances are expected to be more frequent in the future due to climate change.

In Europe, European spruce bark beetle (*Ips typographus* (L. 1758)) is the most problematic pest associated with large disturbance events in forests. Bark beetle outbreaks can last for more than 10 years (Økland & Berryman, 2004). On a landscape scale bark beetle outbreaks are related to the connectedness between bark beetle populations and host plants (Seidl et al., 2015). It was found that larger trees have a high probability of being colonized after a windstorm, and fallen trees were particularly vulnerable to bark beetle attack (Eriksson et al., 2005) regardless of whether the fallen tree still had an intact root system or had been snapped (Eriksson et al., 2008). It is interesting that two years after a windstorm it was observed that standing trees were more frequently attacked but that bark beetles were more reproductive in wind-felled trees (Komonen et al., 2011). Bark beetles mainly attack weakened trees; however, in a large outbreak after a large windthrow, it was observed that bark beetles can also overwhelm healthy trees (Kausrud et al., 2012). When the affected trees are not removed, neighbouring trees are affected, with the peak of the attack occurring in

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a belt of 500 m around the affected area and a gradual decrease in abundance with distance from the disturbed area (Wichmann & Ravn, 2001). However, in areas where sanitary felling had taken place, the attacks in the surrounding areas were not substantially larger than normal (Wichmann & Ravn, 2001). In spatial terms it was found that three years after the disturbance event attacks were still concentrated around areas where the event took place, but that after this period, attacks were still abundant but more focussed in smaller patches (Økland et al., 2016). It was therefore recommended to remove the affected trees within three years after the disturbance event. Interestingly, the increase in brood material during a large disturbance event is such a stochastic, but dramatic event that it is unclear whether other drivers of small outbreaks during the endemic period are still relevant.

Bark beetle management is based on preventive and reactive management (Wermelinger, 2004; Vega & Hofstetter, 2015). Preventive bark beetle management is based on silvicultural management, where the host plant should not be so abundant as to increase the probability of outbreaks, as has already been shown in many cases (Ogris & Jurc, 2010; Pasztor et al., 2014). Reactive bark beetle management deals with short-term measurements when the outbreak is already in progress. Endemic and epidemic periods require different management measures, the use of pheromone traps during the endemic period being an example (Vega & Hofstetter, 2015). In the case of large disturbances it is important to remove the fallen trees of the host plants from the forest as soon as possible so they can no longer be used for brood material (Vega & Hofstetter, 2015). Although these measures seem to work in the epidemic state in the case of small-scale disturbances, there is a need to evaluate the effectiveness of the measures in the event of a large disturbance.

Ice storms occur relatively frequently in Central Europe (Nagel et al., 2016). Most ice storms occur over small surface areas, but occasionally affect large areas. In contrast to other large disturbance events such as windthrows, ice storms leave large numbers of trees standing but damaged, and the affected areas are very patchy and variable in damage intensity (Irland, 2000). Tree species vary in their sensitivity to freezing rain. European beech for instance is very sensitive to trunk breakage or uprooting, while fewer spruce trees were uprooted and relatively more remained standing and damaged (Nagel et al., 2016). After ice storms, the large amount of weakened and fallen spruce trees create an ideal substrate for bark beetles. Subsequent bark beetle outbreak is therefore expected. However, information gained from the patterns and drivers of bark beetle outbreaks after ice storms could also be useful for improving the understanding of disturbance events in general as most other events have been investigated on a local/landscape scale (Wichmann & Ravn, 2001; Komonen et al., 2011; Økland et al., 2016).

From the end of January until the beginning of February 2014, a catastrophic ice storm damaged a large part of Slovenia (Nagel et al., 2016). Around 200 mm of precipitation fell in the most affected areas, and up to 8 cm of ice formed on branches (Sinjur et al., 2014). European beech was the most affected tree species, while conifers such as silver fir and Norway spruce were less affected (Nagel et al., 2016). After the ice storm, there was an attempt to remove the fallen spruce trees from the forest, and sanitary felling of heavily damaged trees took place as a preventive measure against bark beetle outbreaks. By the end of 2014 almost 50% of the fallen conifer trees had been removed (ZGS, 2015). However, a portion of the fallen conifer trees and lightly damaged trees were not removed, and in the following years large bark beetle outbreaks were reported in this area (ZGS, 2016).

Our aim in this study was to investigate the patterns and drivers of bark beetle attacks after the ice storm and to evaluate bark beetle management in the event of a large disturbance. First, we analysed the factors affecting Norway spruce damage due to the ice storm. We then examined the influence of the ice storm damage on the amount of attacked Norway spruce and the spatial patterns of bark beetle attacks. We investigated whether the effects of the drivers of bark beetle outbreaks in the endemic period were reduced due to the ice storm. Furthermore, we evaluated the influence of the amount of spruce and amount of spruce removed as a preventive and reactive measure, respectively, on the potential of bark beetle outbreaks.

2. Materials and methods

2.1. Area description

Forests in Slovenia comprise a surface of 1.2 million ha or around 58% of the surface of the country (ZGS, 2016). Due to its heterogeneous relief, Slovenia has many different forest habitat types, ranging from lowland floodplain forests to mountainous forests. After European beech, the most abundant species is Norway spruce with 30.1% of the total wood stock (ZGS, 2016). The management of the forest is based on close-to-nature silviculture (Diaci, 2006). The ice storm in 2014 occurred mainly in the western part of Slovenia. A large part of the Dinaric Mountains and the Julian Alps were affected by the ice storm (ZGS, 2015). The forests in this area mainly consist of the *Abieti-Fagetum* forest habitat type. The geology of these areas is limestone in both the Dinaric Mountains and the Julian Alps.

2.2. Survey field protocol

For this analysis, we used the ice storm damage data acquired during the field survey of the aftermath of the catastrophic ice storm on January 2014. The survey was designed as a stratified two-stage random sampling due to logistic and financial constraints. Nine strata were used accounting for two criteria: the growing stock per hectare (classified into 3 classes) and the ice storm damage level (also classified into 3 classes). Each stratum was represented by 15 randomly distributed first-stage samples (i.e., $9 \times 15 = 135$ samples), and each first-stage sample consisted of 5 second-stage sampling plots positioned in a zig-zag 100×100 m grid (i.e., $9 \times 15 \times 5 = 675$ sampling plots). At each second stage sampling plot several tree attributes and stand attributes were recorded, including tree species and tree DBH, the form of the tree species mixture, forest stand canopy cover, forest stand developmental stage, slope and exposition, soil depth, and ground surface rockiness (Table 1).

The amount of Norway spruce damaged by the ice storm was extracted from the sanitary felling database of the Slovenia Forest Service, with the forest compartment as the base spatial unit (ZGS, 2014b). Only the sanitary felling of Norway spruce in 2014 and those damaged by the ice storm in 2014 were taken into account when testing the effect of the removal of spruce on bark beetle outbreaks. Data on sanitary felling were linked to the ice storm survey points using Esri ArcGIS 10.4.1 for Desktop (Redlands, CA: Environmental Systems Research Institute). Sanitary felling data within a buffer of 500 m around the ice storm survey point were obtained from the forest compartment database (forest compartment average size is 21.9 ha) (ZGS, 2014a). Additionally, the amount of Norway spruce attacked by bark beetles that was removed was extracted from the sanitary felling database of the Slovenia Forest Service for the years before, during and after the ice storm (2013–2015) (ZGS, 2014b).

2.3. Analysis

We averaged the data of the plots at the level of the first-stage sampling locations. In total, there were 135 locations. Slope, altitude, volume of sanitary felling, basal area of spruce trees and the number of spruce and all trees per damage class were averaged for every location.

For the analysis on the factors influencing the damage to Norway spruce, the classes bent, damaged crowns, and leaning and fallen trees were pooled into one class denoted “damaged trees,” while healthy trees were denoted “not damaged trees”. A generalized linear mixed model (GLMM) with binomial error distribution was used for the