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Drivers of regeneration dynamics following salvage logging and different silvicultural treatments in windthrow areas in Slovenia

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ABSTRACT

We studied regeneration dynamics in forests disturbed by three different windthrow events in 2008 in Slovenia to assess the success of natural regeneration vs planting and subsequent silvicultural treatments. Fifty-three plots with planted saplings of Norway spruce and sycamore maple and 50 plots with dominant naturally regenerated saplings were selected in a randomly stratified manner. Sapling characteristics (height, height increment, root collar diameter, free-to-grow score, browsing and micro-site) were assessed in 2012 and 2014. Herbs and seedling establishment were studied in two subplots within each plot. Average seedling density was 13,074 and 14,674 ha^{-1} four and six years after the windthrows, respectively. Seedlings were irregularly distributed, which suggests micro-site differences in regeneration dynamics. The results indicated lower seedling success on sites that were southerly exposed, farther from the forest edge and seed trees, on undisturbed micro-sites and at higher altitudes. On such sites planting was justified. While seedling density indicated a positive relation to herb coverage, sapling survival was negatively associated with it as well as with browsing. Initial sapling height was the strongest predictor of survival. Spruce saplings had the lowest mortality, while shade-tolerant silver fir and beech experienced high mortality. The study indicated a high density and species diversity of naturally regenerated seedlings within windthrow areas, which was reduced by planting, mowing of competing vegetation and protection measures favouring planted saplings. Recommendations for the improvement of silvicultural operations for post windthrow restoration are given.

1. Introduction

Natural disturbances are an intrinsic part of forest ecosystem dynamics (Pickett and White, 1985). However, they raise concerns for forest owners and managers for several reasons. Their intensity and frequency may be increasing because of environmental changes (Kulakowski et al., 2016). Moreover, many forest stands in Europe are even-aged and monospecific, which make them more susceptible to disturbances (Seidl et al., 2011). Numerous studies have indicated that uneven-aged mixed forests are both more resistant and more resilient to disturbances (O'Hara and Ramage, 2013). However, over the last decade the share of forests damaged by natural disturbances has also been increasing in countries where forests have traditionally been managed with uneven-aged silvicultural systems. For example, in Slovenia several windthrows, ice and snow storms and bark beetle outbreaks resulted in an increase in sanitary logging of a third of the yearly harvest (Diaci et al. 2017). In early 2014 an ice storm of a scale unprecedented in modern history damaged about 9,300,000 m^3 of trees across more than 600,000 ha (Nagel et al., 2017; Čater and Diaci, 2017). The storm was followed by a bark beetle outbreak that claimed almost the same amount of wood.

Besides damage to existing stands, disturbances, especially windthrows, create large openings where different successional stadia develop (Fischer et al., 2002; Wohlgemuth et al., 2002; Jonasova and Prach, 2004; Van Couwenberghe et al., 2011). They may be beneficial for early successional flora and fauna on the one hand, but forest protection functions may be negatively affected on the other (Brang, 2001). Still, in some situations within protection forests, leaving damaged timber in place may be an alternative to silvicultural measures (Schwitter et al., 2015). Windthrow may negatively influence the future income of the forest owner if the share of commercially valuable species is low and regeneration is retarded, and its low density does not enable the production of high quality logs (Diaci et al., 2017). Therefore, spontaneous regeneration of windthrow areas is often supplemented by planting. This can significantly shorten the time period needed to reach closed forest (Schönenberger, 2002; Brang et al., 2004) and to achieve the desired mixture of commercially desirable species. But planting, which often requires protection and tending measures, is expensive and

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may generate problems for the future resistance of stands (e.g. deficient root development, poor match of plant ecotype with site; Balisky et al., 1995). In countries with prevalent close-to-nature silvicultural systems (Pommerening and Murphy, 2004), there has been considerable discussion over the use of artificial versus natural regeneration for the restoration of windthrow areas (Schönenberger, 2002; Schwitter et al., 2015; Brang et al., 2015; Rozman et al., 2015).

Large-scale disturbances after the 1990s prompted extensive research on post-disturbance forest restoration (Mocalov and Lässig, 2002; Ilisson et al., 2007; Peterson and Leach, 2008; Heurich, 2009; Pröll et al., 2015). One of the major outcomes was identification of a great variety of recovery processes that are dependent on the mode and intensity of disturbance, pre-disturbance management, method of restoration and site conditions (Jonasova and Prach, 2004; Rozman et al., 2015). In particular, micro-site variability with pre- and post-disturbance features (disturbed soil, woody debris) may significantly influence regeneration dynamics (Haeussler et al., 2002; Hanssen, 2003; Ilisson et al., 2007; Peterson and Leach, 2008). Any attempt to predict regeneration dynamics should therefore carefully address the many factors that can influence post windthrow regeneration. Lack of seed trees and the absence of the mitigating effect of the forest canopy on the microclimate in open areas, damage to advanced regeneration during salvage logging, development of a the dense herb layer and excessive ungulate browsing are often reported as factors that hinder the development of seedlings (Aussenac, 2000; Hanssen, 2003; Mansourian et al., 2005; Kupferschmid and Bugmann, 2005; Rammig et al., 2007; Van Couwenberghe et al., 2010; Kramer et al., 2014; Brang et al., 2015; Fidej, 2016). The share of pioneer tree species in the post-disturbance succession of spruce dominated boreal and Central European forests is higher in areas that were salvaged and have exposed mineral soil, in larger openings and in stands with stronger past anthropogenic impact (Fischer et al., 2002; Jonasova and Prach, 2004). However, this has not been confirmed in all studies (e.g. Heurich, 2009; Kramer et al., 2014; Fidej, 2016). Newly emerged seedlings may also profit from disturbed soil caused by salvage logging as indicated in studies from Switzerland, Estonia and the eastern USA (Wohlgemuth et al., 2002; Ilisson et al., 2007; Peterson and Leach, 2008).

The amount of coarse woody debris (CWD) within windthrow areas is reduced by salvage logging. However, it is typically more abundant after disturbances than under gradual regeneration felling (cf. Priewasser et al., 2013). CWD represents a seedbed for spruce (*Picea abies* (L.) H. Karst.) and fir (*Abies alba* Mill.) (Eichrodt, 1969; Leibundgut, 1982; Milosavljevic, 2015). Decomposed CWD is required for seedling survival (Kupferschmid and Bugmann, 2005; Zielonka, 2006) but is not available immediately after a windthrow. Therefore, the role of CWD in occupying micro-sites, preventing erosion and protecting seedlings against browsing and competing vegetation is more important (de Chantal and Granström, 2007, Baier et al., 2007, but see Kupferschmid and Bugmann, 2005).

Aspect, slope inclination and altitude jointly alter the effects of climatic and geomorphological factors on tree regeneration. With increasing altitude, the vegetation period shortens, climatic extremes increase, differences between micro-sites intensify (Senn and Schönenberger, 2001; Cunningham et al., 2006) and thus overall forest recovery is retarded (Brang et al., 2004). With increasing altitude and slope inclination, differences in aspect become more ecologically important. Southerly exposed micro-sites are prone to accumulating organic matter and to drying out (Noble and Alexander 1977; Brang, 1998). Slope inclination can also influence snow and water movement, with subsequent erosion processes that may be unfavourable for forest regeneration (Senn and Schönenberger, 2001; Hanssen, 2003; Baier et al., 2007).

Decisions on post-disturbance forest regeneration following salvage logging are often dichotomous: artificial or natural regeneration. While the former involves several silvicultural measures, the latter commonly does not involve any intervention at all. Silvicultural measures improve planted sapling survival (Haeussler et al., 2002; Jacobs et al., 2004) but may drastically decrease the potential of naturally regenerated seedlings. Among these seedlings are ecologically and economically important tree species, which may increase the value of young, sparsely stocked plantations in large open areas after disturbance, especially when planted stock has a high mortality rate. While numerous studies have assessed the impact of salvage logging on post-disturbance regeneration, the impact of post-disturbance silvicultural operations on the development of naturally regenerated seedlings within plantations has rarely been investigated.

The goals of this study were to (1) compare the development of spontaneous seedling establishment within planted areas and areas designated for natural regeneration following windthrow; (2) evaluate the influence of silvicultural operations in plantations on the density, coverage and species composition of naturally regenerated seedlings; (3) compare the success of dominant naturally regenerated saplings with planted saplings; (4) relate regeneration dynamics with abiotic and biotic factors; and (5) to put forward recommendations for the improvement of post-disturbance forest restoration.

2. Methods

2.1. Research sites

In 2008 three windthrows (July 7, 13 and August 15) damaged forests over large areas in west, north-central and east Slovenia (Fig. 1; Anonymous, 2009). The highest volume of damaged trees was in Crnivec (hereafter CRN) in north-central Slovenia followed by Bohor (hereafter BOH) in the eastern part of the country and Trnovski gozd (hereafter TRN, Table 1) in the west. The three windthrow areas differ with respect to climatic conditions and sites (Appendix B). Precipitation decreases along a W-E gradient from TRN over CRN to BOH, while yearly mean temperatures reflect differences in altitude. The TRN and CRN sites were classified as mixed mountain beech (*Fagus sylvatica* L.) and fir forest on carbonate and silicate parent material, respectively, while the BOH area is mostly covered by beech forest sites at different altitudes and on mixed silicate and carbonate parent material (Table 1). Stands damaged by the windthrow were mixed; however, the share of spruce was higher compared to natural conditions (Table 1). The former forests were managed with the irregular shelterwood system (Schütz et al., 2016). Dense, mature stands with average growing stock ranging from 300 to 500 $m^3 ha^{-1}$ were dominant, while established advanced regeneration was sporadically present (Appendix B). Most forests were privately owned, and thus owners were interested in recuperating economic value from disturbed forests as quickly as possible.

In 2008 and 2009 all damaged trees were salvaged and areas designated for planting were planted in 2009 and 2010, while most of the surface was left for natural development. Various species were used for planting, but for comparative reasons we selected only sites where spruce (age 2 + 2) and sycamore maple (*Acer pseudoplatanus* L.) (age 2 + 1) were planted. The individual plantations ranged in size from 0.02 to 1.00 ha. Bare root saplings from local provenances were produced in Slovenia and planted manually in conventional plant holes. The planting density was 1600–2800 saplings ha^{-1} and spacing was regular. Spruce planted saplings were protected from browsing by coating of the terminal shoot, and the surrounding ground vegetation was mowed on a yearly basis. All sycamore maple planted saplings were protected by fine-mesh tubes.

2.2. Field methods

In 2012 we established 53 planting plots (hereafter PP) 10 × 10 m in size in localities where planting took place within the three windthrow areas (Table 1). Planting plots were selected in a randomly stratified manner with windthrow areas as strata. Sites with established clusters of pre-disturbance regeneration, forest roads and skidding roads were avoided (Appendix B, Fig. B.2). In the nearest vicinity possible to the PP, we placed a natural regeneration plot (hereafter NP)