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Tree mortality after wind disturbance differs among tree species more than among habitat types in a lowland forest in northeastern Poland

Jerzy Szwagrzyk[a,*], Anna Gazda[a], Dorota Dobrowolska[b], Ewa Chećko[c], Jakub Zaremba[c], Andrzej Tomski[d]

[a] Department of Forest Biodiversity, Institute of Forest Ecology and Silviculture, Faculty of Forestry, University of Agriculture in Krakow, 29-Listopada 46, 31-425 Krakow, Poland
[b] Forest Research Institute, Department of Forest Ecology, Braci Leśnej 3, 05-090 Raszyn, Poland
[c] Białowieża Geobotanical Station, Faculty of Biology, University of Warsaw, ul. Sportowa 19, 17-230 Białowieża, Poland
[d] Section of Biomathematics, Institute of Mathematics, University of Silesia, Bankowa 14, 40-007 Katowice, Poland

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ABSTRACT

Tree mortality was studied in a 460-ha swath of managed lowland forest that was damaged by a windstorm in July 2002 and set aside for research purposes. The goal of our investigation was to answer three specific questions: (1) Were tree stands in some habitat types more affected by the wind than others? (2) Were some tree species more vulnerable to wind damage? (3) Have smaller trees survived the windstorm better than larger ones? Based on measurements in 111 regularly distributed sample plots, we found that tree mortality amounted to 49% of tree numbers and more than 48% of the basal area. Only two plots were not damaged, and in one sample plot, all trees had been broken or uprooted by the wind. Differences in tree mortality among three major habitat types, apparent in satellite images, were not statistically significant. Scots pine and silver birch displayed significantly higher mortality rates than other tree species, and black alder was least affected by the windstorm. Scots pines were the tallest trees in analysed forest, but statistical analysis employing the odds ratio revealed that these higher mortality rates were not associated with the height difference between the pines and other trees growing in their immediate vicinity. Species composition of the remaining stands was more complex than that prior to the windstorm. We concluded that although salvage logging and replanting with seedlings is the most reasonable option from the point of view of timber production, it is not necessary for saving the integrity of the forest ecosystem and maintaining the continuity of ecosystem services.

1. Introduction

Natural disturbances have been widely recognized as important processes shaping the composition and structure of forest communities (Pickett and White, 1985; Frelich, 2002; Johnson and Miyanishi, 2007; Vanderwel et al., 2013). The role of natural disturbances has been described in various forest ecosystems ranging from boreal (Kuuluvainen, 2002; Rich et al., 2007; Drever et al., 2006) to temperate (Canham et al., 2001; Lindenmayer and Franklin, 2002; Woods, 2004; Nagel et al., 2007) to tropical forests (Lloyd et al., 2009; Tanner et al., 2014). Natural disturbances contribute to the maintaining of tree species diversity (Papaik and Canham, 2006; Marra et al., 2014) by facilitating the persistence of early successional species. They also alter nutrient cycling and carbon sequestration in forests (Vanderwel et al., 2013; Dos Santos et al., 2016), thus affecting ecosystem function and services.

Wind is a common disturbance agent in many forest ecosystems throughout the world (Frelich, 2002; Johnson and Miyanishi, 2007; Mitchell, 2013), but it is especially important in the temperate forest biome (Peterson, 2000; Papaik and Canham, 2006; Fischer et al., 2013), where forest fires are sporadic and limited in extent. Large windstorms, affecting entire regions, are rare (Foster and Orwig, 2006; Schütz et al., 2006; Peterson et al., 2016), but more localized wind disturbances are common and play a major role in gap dynamics (Greenberg and McNab, 1998; Woods, 2004).

Studying the effects of large, intense disturbances in unmanaged forests is difficult. On a global scale, most of these forests are in remote places (Rich et al., 2006; Fraver et al., 2009) and are difficult to access. In Europe, unmanaged forest stands are rare, and they cover small areas (Peterken, 1996; Ulanova, 2000); therefore, studies on the effects of large-scale disturbances in unmanaged areas in Europe are very rare (Wolf et al., 2004; Nagel et al., 2007). However,

* Corresponding author at: Department of Forest Biodiversity, Institute of Forest Ecology and Silviculture, Faculty of Forestry, University of Agriculture in Krakow, 29-Listopada 46, 31-425 Krakow, Poland.

E-mail addresses: rlszwagr@cyf-kr.edu.pl (J. Szwagrzyk), rlgazda@cyf-kr.edu.pl (A. Gazda), D.Dobrowolska@ibles.waw.pl (D. Dobrowolska), e.checko@biol.uw.edu.pl (E. Chećko), andrzej.tomski@us.edu.pl (A. Tomski).

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studying the effects of natural disturbances in managed forest stands is even more difficult. The usual practice in managed forests is to perform salvage logging after a disturbance (Sessions et al., 2004; Foster and Orwig, 2006; Fischer et al., 2015). During logging operations, trees broken or uprooted by wind are cut and removed along with trees that survived the disturbance with some kind of damage. Therefore, there are few comparisons of mortality rates between salvage-logged and unlogged areas (Fidej et al., 2016). The general assumption is that large-scale intensive disturbances kill all trees, which is frequently used for justifying salvage logging operations (Lindenmayer and Noss, 2006).

Several studies carried out in unmanaged stands have shown that tree mortality after wind disturbance varies widely (Canham et al., 2001; Woods, 2004; Nagel et al., 2016) and seldom attains 100% (Peterson, 2000). This can be caused by the spatial variability of wind intensity, which can change even at short distances (Johnson and Miyanishi, 2007). Gusts of wind of extreme speed are usually confined to relatively small areas, and this is reflected by the distribution of forest patches with high mortality levels (Peterson et al., 2016). This phenomenon was pictured well by Doppler radar images of the windstorm "Lothar", showing that wind speeds can produce complex spatial patterns even over relatively flat terrain (Schütz et al., 2006).

Much of the damage caused by wind in the forest is indirect: trees are broken by other trees falling down (Mitchell, 2013). This is especially important is the case of large stems broken or uprooted by wind; these stems can crush many smaller trees on their way down (Peterson, 2000). There are also substantial differences in tree mortality among tree species (Canham et al., 2001; Papaik and Canham, 2006) and habitats with various topographical and soil conditions (de Toledo et al., 2011).

Even in areas affected by severe windstorms, many trees survive disturbances (Peterson, 2000; Lindenmayer and Noss, 2006). Among them are not only trees unaffected by wind but also trees that had been badly damaged that still can rebuild their crowns and live for a long time (Mitchell, 2013). Sometimes the mortality is extended in time; some trees die immediately after being broken, while others, especially among the uprooted ones, die several years later. Thus, conducting studies immediately after a windstorm may lead to underestimated mortality levels.

The knowledge about tree mortality after wind disturbances is still incomplete (Mitchell, 2013), and the opportunities to learn more are limited by the availability of areas where the effects of wind damage can be analysed without confounding effects of salvage logging. An example of a place that allows studying ecological effects of windstorms is the "Szast Protected Forest" (Szast P.F.) in northeastern Poland. In our investigation, we conducted a large-scale survey in the Szast P.F., covering the entire area that was set aside for research purposes after the windstorm in July 2002. Our primary goal was to estimate the extent of mortality resulting from the disturbance and to analyse the variation in susceptibility to wind damage among tree species and habitat types. We asked three specific questions:

(1) Were tree stands in some habitat types more affected by the wind than others?
(2) Were some tree species more vulnerable to wind damage?
(3) Have smaller trees survived the windstorm better than larger ones?

2. Material and methods

2.1. Study area

The investigation was carried out in the Mazury (Mazurkas) Lowlands, which is located in northeastern Poland (21°48′E, 53°38′N). The Mazurkas Lowlands were created by the last Baltic glacial period. Typical for this terrain are numerous lakes, small hills not higher than 190 m a.s.l. and sandy soils. The climate is characterized by changing weather. The mean annual temperature is 7 °C, and the mean annual precipitation is 541 mm. Most of the precipitation falls in the summer. The growing season lasts 190–200 days. The Piska Forest, the object of our investigation, is dominated by Scots pine (*Pinus sylvestris* L.), which occupies 84% of the area. Black alder (*Alnus glutinosa* (L.) Gaertn.), silver birch (*Betula pendula* Roth), and Norway spruce (*Picea abies* (L.) Karst.) cover 16% of the area. The age of the stands ranged from 30 to 70 years.

The northeastern part of Poland was affected by a windstorm in July 2002; it is currently the largest (both by area affected and loss of timber) documented wind disturbance in Polish forests. Wind blew from the south; it lasted approximately 30 min, and the maximum sustained wind speed reached 170 km/h. The wind damaged stands within a belt 15 km wide and approximately 130 km long. The total area of wind-damaged stands was equal to 33 thousand hectares, and the total amount of salvage-logged timber was approximately 3 million cubic metres (Rykowski, 2012). The Piska Forest, especially including the Pisz Forest District, was the most affected area, where 12 thousand hectares of forests were blown down (approximately 2.5 million cubic metres of timber). The salvage logging of the wind-damaged area was completed within one year after the windstorm. The logged areas were then replanted, mostly with Scots pine seedlings. The process lasted 6 years and finished in 2009.

In the eastern part of the Piska Forest, an area of approximately 460 ha in the eastern part of the most affected Pisz Forest District was spared from salvage-logging and left without any intervention. The idea behind that decision was to create an opportunity for studying natural regeneration processes (Rykowski, 2012). In 2003, the Szast Protected Forest was established as a research area. To reduce the risk of fire, the Szast P.F. has been separated from the managed stands by a fire belt 7 m wide. Many studies have already been conducted in the Szast P.F., addressing problems such as the natural regeneration after wind disturbance (Sławski, 2014; Dobrowolska, 2015), spatial structure of wind-disturbed stands (Szmyt and Dobrowolska, 2016) and windthrow impact on forest insect communities (Skłodowski and Zdzioch, 2006) and on bird species (Żmihorski, 2010).

The geographic coordinates of the middle point of the Szast P.F. are 53°33′33.06″N and 21°49′46.69″E. Elevation in the Szast P.F. ranges from 113 to 133 m above sea level. The prevailing soils are Haplic Arenosols (more than 60 plots), Eutri-Fibric Histosols (more than 23) and Haplic Podzols (15 plots).

2.2. Methods of data collection

In the summer months of 2014 and 2015, we established a network of 111 regularly spaced (in a 200 × 200-m grid) circular plots throughout the entire area of the Szast P.F. (Fig. 1). In a first step, we assigned a stand within a plot to one of three categories: severely disturbed, medium disturbed and undamaged/slightly disturbed. For the last category, we applied a plot radius of 10 m (in mature stands) or 7 m (in pole-size stands) for living and dead trees. In severely and medium-disturbed stands, we adopted another approach: we first measured 30 living and dead trees closest to the plot centre with a maximum radius of 10 m (used when there were fewer than 30 individuals in a category). Thus, an actual plot/category radius was the distance from the plot centre to the 30th individual. Within that plot, we measured the diameter of all (both living and dead) trees having a DBH of at least 7 cm. The category of living trees included trees that were strongly bent by wind, trees that were leaning, and trees that had partly dam-