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Sediment transport by uprooting in the forested part of the Tatra Mountains, southern Poland

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ABSTRACT

The process of tree uprooting plays an important role in sediment transport within forested slopes. In this study we determine the intensity of sediment transport by uprooting and its dependencies. We use the Principal Component Analysis (PCA) to determine the most important factors influencing root plate sizes, and we calculate sediment flux by windthrow for the area of the Tatra National Park (211.6 km^2), for the year 2013, when an extreme windthrow event occurred. For this purpose we combine field data with the results of windthrow areas mapping based on satellite imagery. We also use data recorded by the Tatra National Park concerning the amount of destroyed wood in the forests of the Tatra National Park to calculate sediment flux by windthrow for the period between 1968 and 2015 (48 years). To calculate the transport distance by the uprooting needed to compute sediment flux, we modified the Gabet et al.'s (2003) Eq. (11), which in our opinion gives results which are twice the actual size. The PCA identified two the most important factors influencing root plate sizes. The first factor shows that all root plate dimensions increase with increasing tree DBH (diameter at breast height), and, to a lesser degree, with an increase in the content of coarse material. The second factor shows that the depth of a root plate increases with the downslope angle of tree fall, decreasing slope inclination, and decreasing the content of coarse material. The sediment flux by windthrow in 2013 in the area of the Tatra National Park was $3.55 \times 10^{-4}\,m^3\,m^{-1}\,yr^{-1}$. Mean annual sediment flux for the period of the last 48 years was $2.76 \times 10^{-5}\,m^3\,m^{-1}\,yr^{-1}$.

1. Introduction

Tree uprooting is one of the most frequent types of disturbance in forest ecosystems (Schaetzl et al., 1989). The importance and ubiquity of this process in natural forest stands is evidenced by the high percentage of pit and mound microtopography, which may cover from 14.3% (Šamonil et al., 2009) up to 48% (Lyford and MacLean, 1966), or 65% (Kabrick et al., 1997) of a given area, although in managed forests this proportion may be much lower (Šamonil et al., 2010). One of the geomorphological consequences of uprooting is the transport of the soil material attached to the roots of a fallen tree (Denny and Goodlett 1956; Gabet et al., 2003; Lutz, 1960; Norman et al., 1995; Phillips et al., 2008, Phillips et al., 2015). Some studies underline the fact that sediment transport rates under forest conditions may be even higher than those under grassland conditions, and uprooting may be one of the most important processes of transporting sediment on forested hillslopes (Hughes et al., 2009; Pawlik et al., 2013).

Two main stages of sediment transport by uprooting may be distinguished. The first one is the movement of the sediment within a root plate when a tree is toppled, and the second is the transport of the sediment by the action of superficial processes, which cause the erosion of soil exposed in the created root plate/mound (Gabet et al., 2003; Gallaway et al., 2009). A way to assess the distance of the first stage of transport was presented by Gabet et al. (2003). During the second stage some part of the sediment may fall back into the pit. Norman et al. (1995) found that on slopes above 47° the whole sediment in a root plate falls outside the pit.

Many factors influence the rate of sediment transport by uprooting. The first one is the intensity of uprooting, which may occur as small events, including the fall of a single tree or several trees, or as extreme events creating large windthrow areas. The latter, however rare, become significant in longer timescales (Šebková et al., 2012). Also the type of tree damage (uproot, trunk breakage) is important, because trunk breakage does not cause sediment transport. Published proportions between broken and uprooted trees differ among sites, ranging from 14% up to 59% of uproots (Pawlik, 2013a). In the case of uprooted trees, the direction of fall plays an important role in the distance of sediment transport (Gabet et al., 2003). Besides these factors, the

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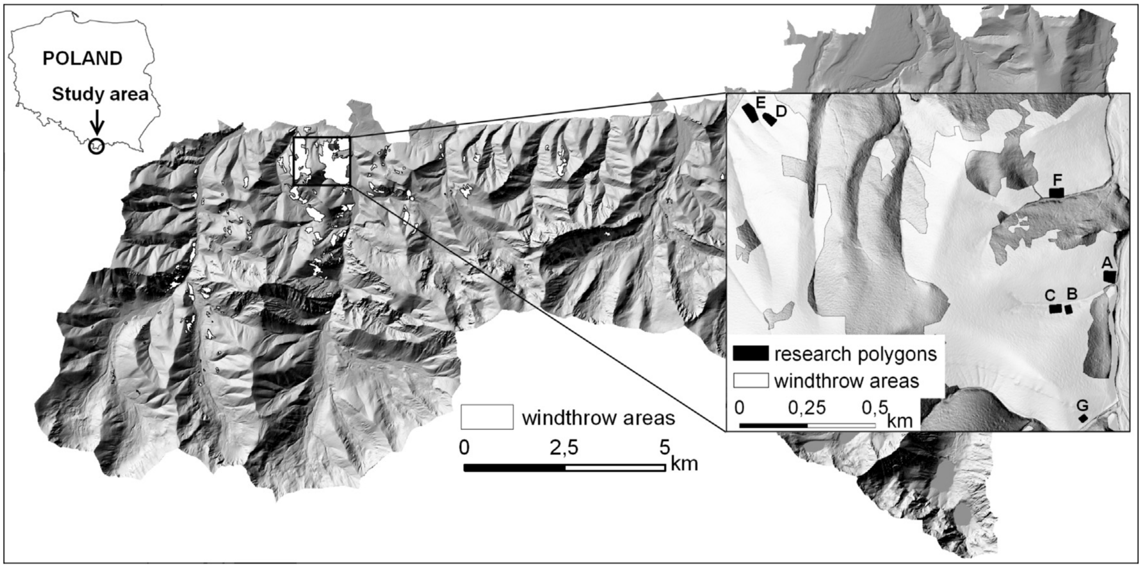

Fig. 1. Location of the Tatra National Park, windthrow sites, and the research polygons.

amount of the sediment uplifted by a single root plate is also important. The primary factor influencing root plate or pit dimensions is the size of the tree (Lenart et al., 2010; Phillips et al., 2015; Putz, 1983), although this relationship is not always as strong as could be expected (Phillips et al., 2008). There are some remarks pointing to the influence of other factors such as the slope inclination or fraction of soil waste material (Dąbrowska, 2009; Gallaway et al., 2009; Strzyżowski et al., 2016). Also the morphology of a root system may influence the shape of a root plate, and thus its dimensions (Fourcaud et al., 2008).

There were attempts to calculate sediment flux by windthrow. The results of these studies vary, and show transport at the order of magnitude from 10^{-3} to 10^{-5} m^3 m^{-1} yr^{-1} (Constantine et al., 2012; Gabet et al., 2003; Gallaway et al., 2009; Pawlik et al., 2013, 2016). Such calculations require data on the intensity of windthrow events. For this purpose, some geomorphic works are based on the rates of tree fall presented in other studies. However, the results of these studies vary significantly. Faliński (1978) reported a tree fall rate of 8–13 trees ha^{-1} yr^{-1} for lowland forests in Poland. Mills (1984) estimated a fall rate of 8 trees ha^{-1} yr^{-1} for the eastern USA. Significantly lower values were obtained by Naka (1982), and Brewer and Merritt (1978): 0.84 trees ha^{-1} yr^{-1} for forests in Japan, and 0.13 trees ha^{-1} yr^{-1} for forests in the northern USA, respectively. For old-growth forest in the Czech Republic 1.5 trees ha^{-1} yr^{-1} was noted (Phillips et al., 2017; Šamonil et al., 2009). In spite of these differences, Jonsson and Dynesius (1993) pointed that many studies providing estimations of tree fall rates are based on short term (< 10 years) observations, and this may lead to overestimations in the provided results. It is also important that some studies cover small areas of a plot level, and although there were many works which underlined the role of tree uprooting in the transfer of sediment within a hillslope, little attention has been so far paid to the geomorphic role of this process on a regional scale. In this study we want to fill this gap, and show the regional-scale geomorphic role of tree uprooting by calculating the rate of sediment transport by windthrow for the whole Polish part of the Tatra Mountains. We base our study on field research, but we support our results by GIS analyses of a broader area, and the recorded magnitude of damage in the forests of the Tatra National Park for the last 48 years. Also, given many factors which may influence root plate sizes, we want to determine which of them are the most important. We intend to attain the three following objectives: (1) to define the most important factors which controlled the sizes of root plates, (2) to determine the sediment flux by windthrow in 2013 for the whole area of the Polish part of the Tatra Mountains, including the proportion between the trees fallen upslope and downslope, and (3) to calculate the mean annual sediment flux and turnover time by windthrow for that area, for the period of the last 48 years.

2. Study area

The research was conducted in the Polish part of the Tatra Mountains, in the Tatra National Park (TPN). The total area of the TPN is 211.6 km^2. As a result of the occurrence of glaciers in the Pleistocene period, the relief of the southern part of the area has a typical high-mountain character (Kotarba et al., 1987). The highest summits reach a height of over 2400 m a.s.l. The northern part of the area is characterised by the middle-mountain relief (Klimaszewski, 1988). The southern part is built of metamorphic rocks, while the northern part of sedimentary rocks (Bac-Moszaszwili et al., 1979).

The mean annual temperature for the forested part of the Tatras ranges from 4 to 2 °C, and the mean annual rainfall is between 1400 and 1600 mm (Hess, 1974). The mean annual wind velocity (Kasprowy Wierch, 1987 m a.s.l.) is 6.3 m s^{-1}, and the mean number of days with a wind velocity exceeding 15 m s^{-1} is 62 (Niedźwiedź, 1992).

The natural forest structure in the Tatra Mountains includes deciduous forest, with the dominance of beech, up to 1200 m a.s.l., and coniferous forest, mostly composed of spruce, which reaches the upper timber line at the height of 1550 m a.s.l (Mirek, 1996). However, owing to human impact, the structure of the deciduous forest belt has been changed, and it is mostly composed of spruce (Ciurzycki, 2003; Skawiński, 1996).

The Tatra Mountains were affected by a strong foehn wind event on 25 December 2013. The maximum hourly average wind speed exceeded 100 km h^{-1} (29 m s^{-1}), and the dominant wind direction was from the south (according to data from the Institute of Meteorology and Water Management). The event resulted in the formation of large windthrow areas, mostly within the Kościeliska and Lejowa valleys. After the event, within about half of the windthrow area (including the area of the research polygons), salvage logging was conducted by cutting off trunks at the base of the trees.

The field work was conducted within 7 research polygons located within the Kościeliska Valley and the Lejowa Valley – the areas most severely affected by the windthrow event in 2013 (Fig. 1). The area of the polygons ranges from 0.06 to 0.21 ha, and totals at 0.97 ha. Two of the polygons are located within conglomerate, four of them within limestone and marls. The soils within the polygons are Eutric Cambisols, with a mean depth of 1 m, and Cambic-Rendzic Leptosols, with a