GEOMORPHOLOGICAL CHANGES WITHIN A HILLSLOPE CAUSED BY A WINDTHROW EVENT IN THE TATRA MOUNTAINS, SOUTHERN POLAND

DARIUSZ STRZYŻOWSKI[1], JOANNA FIDELUS[2] and MIROSŁAW ŻELAZNY[1]

[1]Institute of Geography and Spatial Management, Faculty of Biology and Earth Sciences, Jagiellonian University, Cracow, Poland
[2]Institute of Geography, Pedagogical University, Cracow, Poland

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ABSTRACT. Tree uprooting plays an important role in hillslope evolution. The geomorphological impact of tree uprooting after a foehn wind occurrence, in December 2013 in the Tatra Mountains, was investigated. Geomorphological mapping was conducted in three watersheds. Additionally, in one of the watersheds, 459 windthrow pits were measured, in an area of 6.4 ha. The mean volume of a pit was 2.41 m^3, and the mean surface area was 5.47 m^2. 3.9% of the area was affected by windthrow pits, however locally the magnitude of changes was significantly higher, reaching up to 14.5% of the surface area. Slope inclination weakly influenced the effects of uprooting, and a decrease in the average depth of pits on steep slopes was observed. Individual windthrow pits (five cases) initiated the activity of geomorphological processes, and two cases of periodic springs were noted. Changes in the relief of small landforms caused by tree uprooting were documented. Windthrow creation facilitated the delivery of the soil material from the slopes into the channels.

Key words: windthrow event, hillslope processes, relief changes

Introduction

Tree uprooting has been shown as an important geomorphic process which entails many consequences in relief evolution. When a tree is uprooted, the soil material attached to the root system is transported (Denny and Goodlett 1956; Lutz 1960; Kotarba 1970; Schaetzl *et al.* 1989; Gabet *et al.* 2003; Phillips *et al.* 2008; Gallaway *et al.* 2009; Walther *et al.* 2009; Šamonil *et al.* 2010; Constantine *et al.* 2012; Pawlik *et al.* 2013; Phillips *et al.* 2015). In the place where the tree was standing, a surface devoid of vegetation cover is created (Phillips *et al.* 2008; Hancock *et al.* 2011), which potentially exposes the slope to landsliding, slope wash, and gully erosion (Kotarba 1970; Gerber *et al.* 2002; Hancock *et al.* 2011). After a tree fall, a pit and a root plate are created. Subsequently, the root plate, which consists of the root system of the fallen tree and the soil material, is transformed into a mound by the decomposition of the roots, and denudation of the soil material (Schaetzl and Follmer 1990; Pawlik 2013). Therefore, time needed to form the mound is different depending on the intensity of the superficial processes denuding the soil material and the rate of wood decomposition. The latter was shown to last for 50–60 years for beech trees (*Fagus sylvatica*) in temperate forests of Central Europe (Šamonil *et al.* 2009). Finally, a specific microrelief of pits, in the place where the tree was standing, and mounds, in the place where the soil material attached to the root system was deposited, are created (Denny and Goodlett 1956; Norman *et al.* 1995; Pawlik *et al.* 2013). The creation of the microrelief may depend on slope inclination, and on the direction and type of tree fall. Within gentle slopes, or in the case of an uphill windthrow, the soil material from the root plate may fall back into the pit and a microrelief may not be formed (Norman *et al.* 1995; Gabet *et al.* 2003; Gallaway *et al.* 2009). The same situation may occur in the case of rotational fall (instead of the other type: hinge), when the root plate may slide back into the pit (Beatty and Stone 1986; Bobrovsky and Loyko 2016). Considering longer timescales, complete soil turnover, which is a period needed for windthrows to affect the entire surface of an area, can occur at an interval of 11 235 years (Phillips and Marion 2006), 2777 years (Lenart *et al.* 2010), or 1250 years (Šamonil *et al.* 2009). Therefore, significant changes in the structure of soils occur

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(Schaetzl 1986; Small *et al.* 1990; Osterkamp *et al.* 2006). In many cases, the occurrence of windthrows in an area also triggers human activity through salvage logging, which may induce some other geomorphic effects (Gerber *et al.* 2002; Roberts *et al.* 2004).

Literature provides examples of areas where tree uprooting occurs as a severe event, affecting most trees in a given area (Phillips *et al.* 2008, 2015), and areas where single windfalls occur (Šamonil *et al.* 2009). Apart from the frequency and areal extent, geomorphic effects of a windthrow event are influenced by many biotic and abiotic factors. The amount of soil material displaced during a windthrow event may depend on the species of a tree, e.g. conifers were shown to be more vulnerable to uprooting than hardwoods (Phillips *et al.* 2008; Lenart *et al.* 2010). The dimensions of the root plate can be influenced by the size of a tree, type of soil cover, or slope inclination (Clinton and Baker 2000; Phillips *et al.* 2008, 2015, Gallaway *et al.* 2009; Lenart *et al.* 2010).

Some studies attempted to answer the question whether areas affected by a windthrow event encounter more intense denudation rates (Gerber *et al.* 2002; Hancock *et al.* 2011; Pawlik 2012). Hancock *et al.* (2011) and Pawlik (2012) showed no increase in slope wash activity and no gullying initiation, or other evidence of sediment movement within windthrow areas. However, Gerber *et al.* (2002) reported an increase in the landslide rate after a windthrow event. This shows that results are not consistent and further examination is needed.

A small number of studies are concerned with the impact of uprooting on the transformation of existing landforms. Jackson and Sheldon (1949) observed the detachment of rocks from the valley side by roots of yews, but they linked this process with root growth, rather than uprooting. There are also some remarks which underline the impact of pit and mound microtopography on the change of slope profile roughness (Lyford and MacLean 1966; Pawlik *et al.* 2013). Another study presented by Embleton-Hamann (2004) provides an example of windthrow pits which have been significantly enlarged by karst processes.

The process of uprooting was a subject of many studies at different sites. However, it appears that its geomorphological consequences are still not fully recognized. The main aim of this article is to identify the geomorphological changes within the slopes of the Tatra Mountains caused by a windthrow event. It was achieved by realizing the following objectives:

(1) recognizing the changes in the relief of landforms (e.g. shallow landslides, hollows, lateral undercuts) caused by tree uprooting;
(2) defining the dimensions of created windthrow pits and their variability connected to slope inclination;
(3) identifying the distribution of the magnitude of changes across the hillslope;
(4) determining whether a windthrow event caused an increase in the activity of slope processes.

Study area

The study area is located in the Tatra Mountains, in southern Poland, within the Tatra National Park. According to their geological structure, the Tatra Mountains can be divided into two parts, that is, the southern part built of crystalline rocks and the northern part built of sedimentary rocks (Bac-Moszaszwili *et al.* 1979). The study area is located entirely in the sedimentary part which is characterized by fluvial-denudation relief (Klimaszewski 1988).

The research was conducted in three watersheds located within the Kościeliska Valley (Fig. 1). The areas of the watersheds are as follows: 22.6 ha (study site I), 14.7 ha (study site II) and 78.2 ha (study site III). The elevations in the study area range from 926 to 1333 m a.s.l. The average slope inclination is 28°. Two of the studied watersheds (II, III) are composed of limestone and marl, and one (I) of conglomerates and dolomitic sandstone (Bac-Moszaszwili *et al.* 1979).

Dominant types of soils include Cambic-Rendzic Leptosols and Eutric Cambisols. In general, the depths of these soil layers are 0.5 m and 1 m respectively (Skiba 2002). The matrix is generally silty loam with a changeable content of cobbles and gravels, increasing with depth.

The average annual temperature in the study area ranges from 2 to 4°C. The mean annual rainfall is 1400–1600 mm, with maximum monthly values from June to July. The Tatra Mountains encounter frequent foehn wind occurrence, with the largest amount of events noted in November (11 events), December (10 events) and January (9 events). Foehn wind velocities can reach up to 60 m s^{-1} on the slopes, and 25–30 m s^{-1} in the valleys (Hess 1974; Niedźwiedź 1992).

A windthrow event occurred on 25 December 2013. The synoptic situation was typical for a foehn phenomenon, with a low pressure system situated in North-Western Europe and a high pressure system in South-Eastern Europe. The maximum hourly

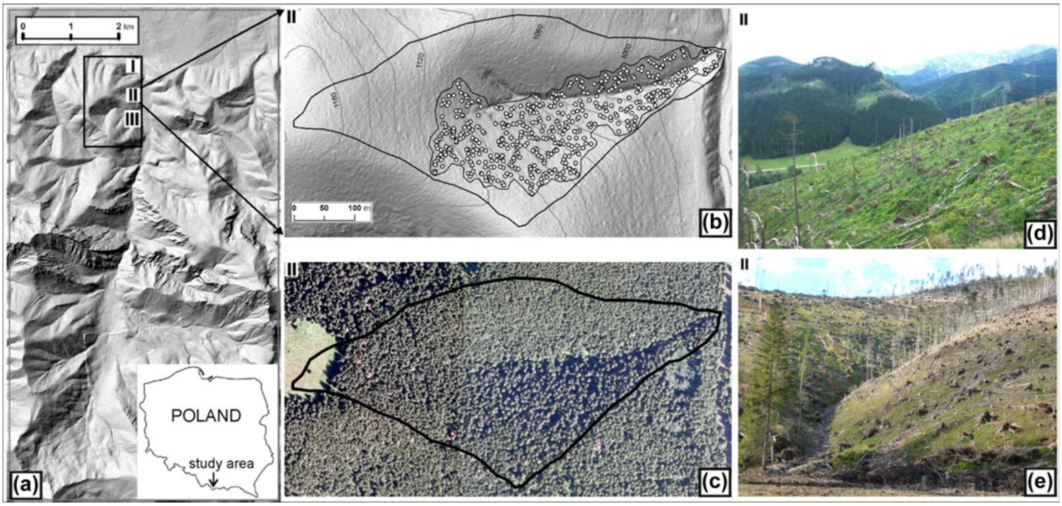


Fig. 1. Location of the study area within the Kościeliska Valley (a). Study site II with the measured windthrow pits marked as dots (b). An ortophoto of study site II, presenting the watershed before the windthrow event (CODGiK, http://www.codgik.gov.pl/index.php/zasob/ortofotomapa.html, 10-Dec-15) (c). Photos of study site II after the windthrow event (d, e).

average wind velocity reached 29 m s^{-1}. During a period of 5 hours, the maximum average velocities exceeded 25 m s^{-1} (data obtained from the Institute of Meteorology and Water Management). As a result, 57% of the forest stand was destroyed in study site I, 96% in study site II, and 25% in study site III (data obtained from the Tatra National Park).

After the windthrow event, the removal of the fallen trees was conducted in the summer season. Trunks were cut off at the base of the trees, and they were transported mostly in suspension using the cable logging method. Despite sawing off the trunks, no cases of root plates rotating back into the windthrow pits, noted by Phillips *et al.* (2008, 2015), were observed. After the removal of most of the trunks, the planting of new trees took place in each study site within the areas where logging was conducted. Both logging and planting increased the area devoid of vegetation.

The natural forest in the study area should be mostly composed of deciduous trees with the dominance of beech (*Fagus sylvatica* L.), however, due to human impact, natural forest stands were destroyed (Fabijanowski and Dziewolski 1996). The study area is dominated by the Norway spruce [*Picea abies* (L.) H. Karst] with rare occurrences of the European silver fir (*Abies alba* Mill.). Most of the forest stands exceed the age of 100 years, and may be as old as 140 years (Przedsiębiorstwo Wielobranżowe Krameko 2005).

Methods

Field work

In the first stage of the study, detailed geomorphological mapping of three study watersheds (I, II, III) was conducted in order to realize objective 1 (see section Introduction). Landforms were measured using a measuring tape, and their location was marked using a GPS receiver. Additionally, at this stage of research, we mapped any windthrow pits or root plates which caused evident changes in the relief of mapped landforms.

In the next stage of the study, for the implementation of objectives 2, 3 and 4, windthrow pit measurements were conducted within study site II (Fig. 1), which encountered the most severe windthrow damage. We analysed 44% (6.4 ha) of the watershed area, located mainly on the right side of the valley (Fig. 1B). We did not analyse the rest of the valley because logging operations were not conducted within that area, therefore, the field difficulties precluded accurate measurements. Width, length, depth and slope inclination were measured for every windthrow pit using a measuring tape and an inclinometer. The width of each pit was measured along its axis perpendicular to the direction of tree fall. The length was measured along the axis parallel to the direction of the tree fall. The depth was measured at the deepest point of the pit. The location of every windthrow pit was marked by a GPS

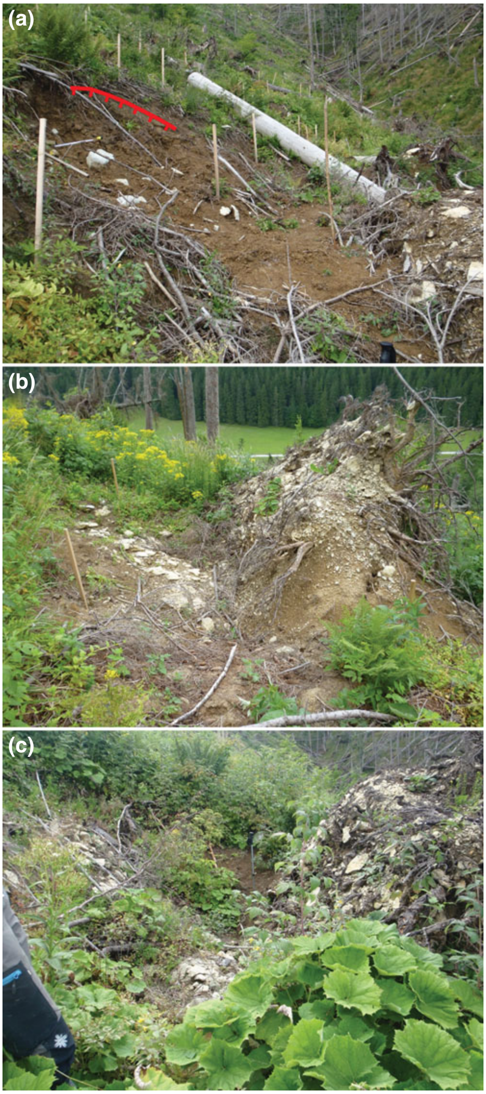


Fig. 2. Example of active (a), potentially active (b) and inactive (c) windthrow pits.

receiver. Additionally, all windthrow pit surfaces were classified into three categories according to the observed signs of geomorphological activity within them. The categories included active, potentially active, and inactive pits (Fig. 2). A pit was classified as active if its surface was less than 30% vegetated, and any signs of geomorphic activity or water phenomena were observed. The potentially active category was attributed to pits with a surface that was less than 30% vegetated, and presented no visible signs of geomorphological activity. Pits classified as inactive were more than 30% vegetated. The percentage of vegetation within the pits was assessed visually. In total, 520 windthrow pits were identified. In some cases, because of dense vegetation or changes caused by logging operations, the location of the edge of a pit was uncertain, thus 459 pits were measured. We focused mainly on windthrow pit measurements, rather than those of root plates, as a feature which better reflects relief change. Additionally, we measured and marked, using a GPS receiver, the area of all surfaces devoid of vegetation, created by human activity (logging and planting; see section Study area) that occurred after the windthrow event. Most of the field work was conducted in July 2015, 1.5 years after the windthrow event. Some additional measurements (mapping of windthrows in the vicinity of a channel; see section Results) were realized in June 2016.

Data analysis

Measuring the windthrow pits allowed us to calculate their volume and the surface area they occupied. The volume of the pits was determined based on the Norman *et al.* (1995) formula which approximates the shape of the pit to a half of an ellipsoid. The formula is:

$$V = (\pi wld)/6 \quad (1)$$

where w is the width, l is the length and d is the depth of a windthrow pit. The surface area of a single windthrow pit was determined based on the formula:

$$A = \pi wl/4 \quad (2)$$

where A is the area of a single windthrow pit.

In order to determine the diversity of changes within the hillslope, study site II was divided into a regular square (20 × 20 m) network. The square network was set in a planar view, therefore the real surface area for each square was calculated and ranged from 431 to 550 m^2. Then, a line bordering all measured windthrow pits was created. All squares which were located beyond the line, or intersected it, were excluded. Ultimately, 76 squares containing 307 windthrow pits were established. For each square, the percentage of surface area occupied by pits and the thickness of the removed soil layer were determined.

To find the relationship between dimensions of windthrow pits and slope inclination, Pearson's linear correlation coefficient was used. To determine significant differences between the average

Table 1. Number of landforms mapped within each study site.

	Study site I	Study site II	Study site III
Shallow landslides	6	6	5
Pits within the edge of a shallow landslide	3	2	1
Hollows	8	3	13
Pits within the edge of a hollow	–	2	–
V-shaped valleys	2	1	5
Lateral undercuts	16	10	23
Pits within the edge of a lateral undercut or in the direct vicinity of a channel	8	16	7
Tors	–	–	11

dimensions of the pits within nine slope inclination groups, an *analysis of variance* (*ANOVA*) was conducted. To compare the differences between averages, the F-Snedecor test was used. Later, the Sheffé *post-hoc* test was used to identify which averages vary significantly.

The normality of variable distribution was checked using the Kolmogorov–Lilliefors test. If variables did not present normal distribution, transformation ($\log_{10}$) was used. If log-transformed variables still did not present normal distribution, the skewness coefficient before and after the transformation was compared for each variable. A variable which presented a lower skewness coefficient was used for further analysis. All variables were standardized. A significance level of $p = 0.05$ was assumed for all statistical analysis.

For the purpose of statistical analysis we used Statistica 12 software, and GIS analysis was conducted using ArcMap 10.2.

Results

Changes in the relief of existing landforms

The geomorphological mapping conducted in study sites I, II and III provided examples of changes in the relief of shallow landslides, hollows and lateral undercuts, caused by uprooting. In total, 17 shallow landslides were identified (Table 1) with an area ranging from 17 to 115 m^2. Two of the landslides with areas of 17 m^2 and 19 m^2 were unvegetated, therefore they had probably been created after the windthrow event. In six cases, a windthrow pit was created at the edge of the shallow landslide scarp (Fig. 3). There were four cases where a windthrow pit was created in the peripheral part of the landslide scarp, and two cases where a pit was created within the upper part of the landslide scarp. Such situations caused changes in the shape of the landslide scarps. If the landslide width is 7 m, and the width of the pit is 3.6 m, the eventual change of the landform can be significant (Fig. 3). Figure 4 presents the schematic types of impact of uprooting on shallow landslide scarps.

Fig. 3. Field example of a windthrow pit which occurred in the direct vicinity of a shallow landslide.

A situation similar to that presented in Fig. 4 occurred within small hollows (magnitude one; see Dietrich *et al.* 1987). There were two cases in which, like in the case of landslides, the pit was created within the peripheral and upper edge of the landform.

A different situation was observed in study site II, where two trees growing close to each other were uprooted downslope, creating one pit up to 10 m wide. After the complete deterioration of root plates, the created mound may resemble a colluvium and the created pit may resemble a landslide niche. In study site II, we identified one landform which probably had such a genesis.

In the whole study area, we noted 49 lateral undercuts (Table 1), with an area of 428 m^2, from which soil material may be delivered into the channels. This area was broadened by 31 windthrow pits (with a total area of 176 m^2) created at the edge of a lateral undercut, or in the direct vicinity of a channel (Fig. 5). We also noted 16 cases of root plates fallen into a channel and 12 cases where the soil material from the root plate was able to fall directly into a channel.

Windthrow characteristics and the distribution of changes

In study site II, where windthrow pit measurements were conducted, the whole forest stand was destroyed, excluding a few trees located on the

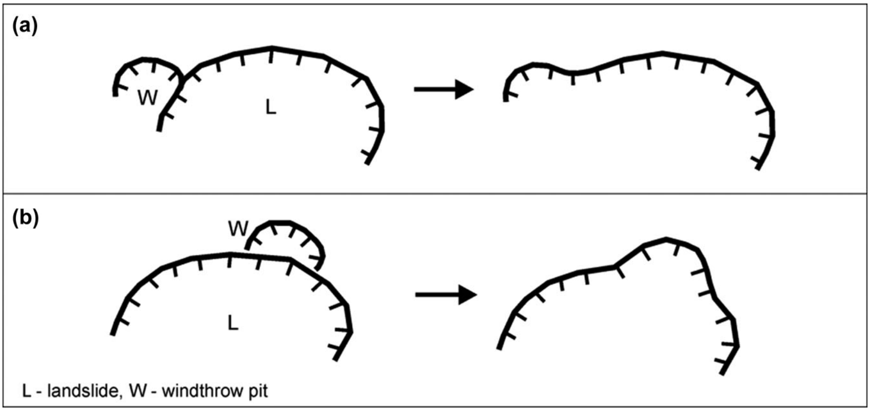


Fig. 4. Schemes showing possible changes within a shallow landslide as an effect of a windthrow occurrence within the peripheral part of a landslide scarp (a) and within the upper part of a landslide scarp (b).

Fig. 5. Example of a windthrow pit from which slope material has been washed into a channel (a). Example of a root plate and a windthrow pit created in the vicinity of a channel (b).

left side of the valley. We do not have precise data concerning the proportion of uprootings versus snaps and the angle of the tree fall, however we observed that uprooting was the most frequent type of damage and that most of the trees fell downslope. Of all the destroyed trees, most of them were uprooted and a small proportion of them were snapped. The mean surface area of a single windthrow pit is 5.47 m^2, and the mean volume is 2.41 m^3 (Table 2). The total surface area occupied by freshly created pits covers 3.9% of the research area (Table 3), of which 1.6% are active and potentially active pits, and 2.3% are inactive pits. Additionally, 0.9% of the research area is devoid of vegetation due to human

Table 2. Basic characteristics of the measured windthrow pits within study site II.

Characteristics	Pit area (m^2)	Pit volume (m^3)
Minimum	0.94	0.14
$\text{Decile}_{10\%}$	1.98	0.59
$\text{Quartile}_{25\%}$	3.14	0.96
Mean	5.47	2.41
Median	4.87	1.88
$\text{Quartile}_{75\%}$	7.25	3.30
$\text{Decile}_{90\%}$	9.83	5.04
Maximum	15.11	11.53
Standard deviation	3.00	1.88
Total	2509.82	1104.82

Table 3. Basic characteristics of the windthrow area within study site II.

Category		Value
Research area (ha)		6.4
Measured windthrow pits (*n*)		459
Number of windthrows per ha (n ha^{-1})		72
Surface area occupied by pits (%)		3.9
Unvegetated surface area (human impact) (%)		0.9
Windthrow pit area per 1 ha (m^2 ha^{-1})		391.5
Windthrow pit volume per 1 ha (m^3 ha^{-1})		172.4
Hypothetical layer of disturbed soil mantle (cm)		1.7
Number of windthrow pits (*n*)	active	5
	potentially active	150
	inactive	304

impact. The volume of measured windthrow pits per 1 ha is 172.4 m^3. If spread evenly across the area, it would create a soil layer that is 1.7 cm thick.

Of all 459 windthrow pits, 304 (66%) were classified as inactive, 155 (33%) were classified as potentially active and 5 (1%) were classified as active. Active windthrow pits presented effects of micro-scale landsliding and periodic spring activity (two cases), micro-scale landsliding (one case) and permanent spring activity (two cases). However, it was hard to determine if the permanent springs were activated by windthrows. It is more probable that they were present before the event, in the vicinity of the trees.

The square network we had created provided us with a more detailed insight into the effects of the windthrow event within the slope. The magnitude of the changes is not uniformly spread across the slope. Areas strongly affected and areas with little or no disturbance can be determined (Fig. 6). For example, the maximum value for the surface area occupied by pits, based on the square network, is 14.5%, and the minimum value (excluding two squares which did not contain any windthrows) is 0.67%. The same pattern is observed in the case of a hypothetical layer of disturbed soil mantle (Table 4).

Influence of slope inclination

Significant but very weak relationships were found between slope inclination and pit length ($r = 0.19$), pit depth ($r = -0.22$) and the width to length ratio ($r = -0.27$; Fig. 7). Regarding pit width, pit area and pit volume, no significant correlations with slope inclination were found.

Considering the abovementioned weak relationships between the presented parameters, the differentiation of the average pit length, pit depth and the width to length ratio in relation to slope inclination divided into nine groups (3° intervals) was identified using ANOVA and the Sheffé test.

The average pit length varies significantly between only two groups of slope inclinations: 27–29° and 36–38° (Fig. 8). The average pit depth presents a more slope-dependent pattern. Within the steepest slopes (>38°), windthrow pits with the lowest average depths occur, and they vary significantly from the average depths of the pits located within gentler slopes (18–32°). No significant difference between the highest and lowest slope inclination groups is probably due to the small number of variables in the first group (>18°). The average ratio of width to length varies significantly between the pits located on the slopes above 36° and those located on the slope inclinations between 18 and 32°.

In addition, the ratio of active and potentially active to inactive windthrow pits changes with slope inclination. Figure 9 shows that above the inclination of 33° the proportion of active and potentially active pits increases; however, within gentler slopes this trend does not occur.

Discussion

Relief changes

Extreme geomorphological events in the study area occur relatively frequently, and most of them are caused by high-intensity rainfall. During these events, the highest magnitude of changes is observed in the valley floors and colluvial-alluvial fans (Gorczyca *et al.* 2014). Our study is an example of a different extreme event, which also caused significant geomorphological changes affecting the whole hillslope.

The literature presents little information on the impact of windthrows on the relief of other landforms. There are only general remarks considering the pit and mound creation within a hillslope (Denny and Goodlett 1956; Lyford and McLean 1966; Norman *et al.* 1995; Kabrick *et al.* 1997), which leads to increased surface roughness (Pawlik *et al.* 2013). Based on our results, we find that windthrows may contribute to changes in the relief of small landforms. The most frequent changes were observed in the case of shallow landslides and lateral undercuts.

In the study area, scarps of 6 of 17 (35%) shallow landslides were affected by a windthrow pit. In the Oregon Coast Range, Roering *et al.* (2003) noted that in many cases trees grew at a close distance from a landslide scarp. They reported

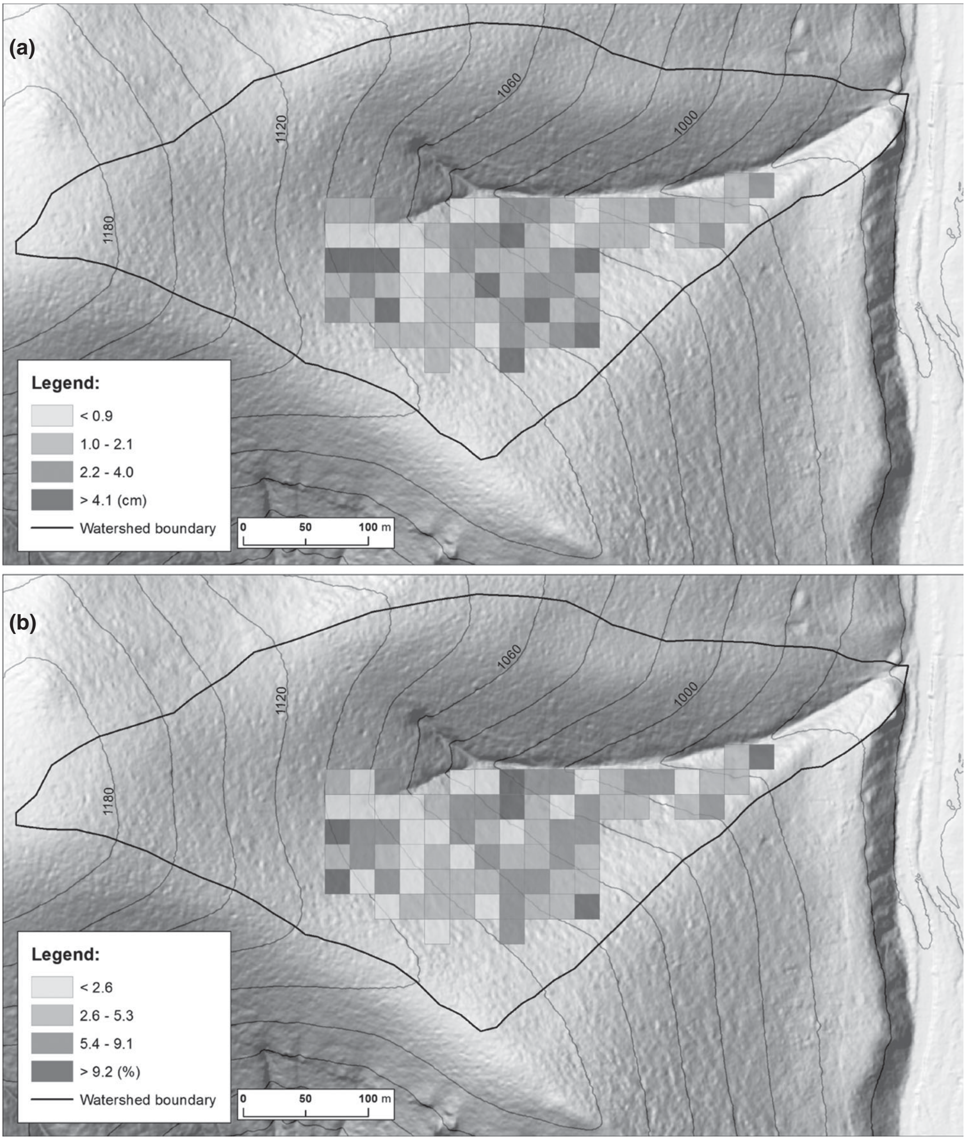


Fig. 6. Spatial distribution of windthrow effects within study site II. Hypothetical layer of the disturbed soil mantle (a). Percentage of the surface area occupied by windthrow pits (b).

that tree roots significantly decrease susceptibility to shallow landsliding and, therefore, landslides may occur at some distance from a tree, where the root reinforcement is weaker. Taking this fact into consideration, it is probable that changing the relief of shallow landslides by creating a windthrow pit near the shallow landslide scarp may occur relatively frequently within windthrow affected hillslopes. Such situations should be taken into account in measuring small landslides in areas with a high intensity of uprooting events. In many cases mound creation would point to a windthrow occurrence; however, in some cases it could cause problems in interpretation. It seems that different situations can occur when two or three windthrows create one pit and one root plate, which was also reported in other studies (Kotarba 1970; Clinton and Baker 2000). After the complete deterioration

Table 4. Windthrow site characteristics calculated for particular squares within the square network that was created.

		Hypothetical layer of the disturbed soil mantle (cm)	Surface area occupied by pits (%)
Square values	Minimum	0.2	0.67
	Median	1.8	4.16
	Mean	2.2	4.84
	Maximum	6.8	14.50

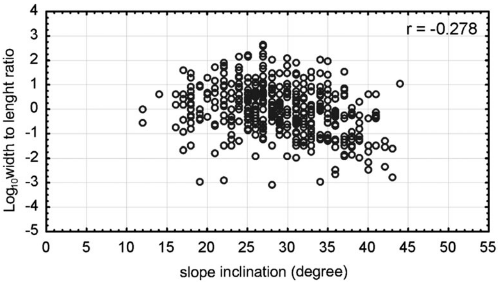


Fig. 7. Negative correlation between slope inclination and the width to length ratio.

of the root plate, it can be hardly distinguished from a shallow landslide.

The occurrence of windthrows within the edge of lateral undercuts or in the proximity of a channel was equally frequent. This increased the amount of soil material which may be transported from the slopes directly to the channels.

We observed only two cases in which created windthrow pits affected the relief of hollows, therefore the modelling of these landforms by uprooting occurs rather infrequently.

The magnitude of changes and their distribution

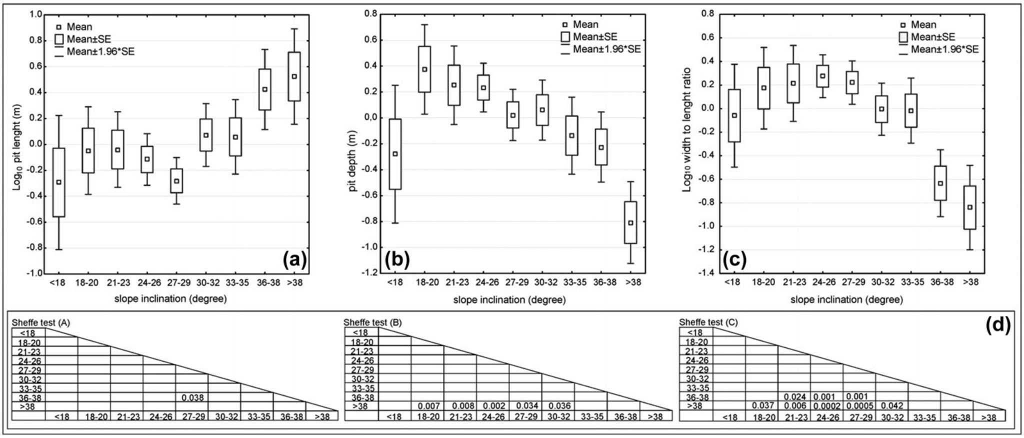
The reported characteristics of windthrows are generally of the same order of magnitude as the values obtained in other studies (Table 5). The values obtained for the Tatra Mountains by Kotarba (1970) and Rojan (2010) are also similar. However, they present a higher amount of uplifted material per 1 ha because of a denser forest stand, which is reflected in the number of windthrows per ha (Fig. 3).

Many studies underline the spatial variability of windthrow occurrence and its consequences (Cremeans and Kalisz 1988; Phillips and Marion 2005, 2006) despite the regular temporal occurrence of windthrow events (Šamonil *et al.* 2009). Our results show a non-uniform distribution of changes within a hillslope caused by one severe windthrow event. Such a situation is not surprising, taking into account the complexity of the forest stands. However, it is worth noting that the maximum value of the surface area occupied by windthrow pits is 14.5%. If we double it, assuming that sediment deposition from the root plate will create a mound of the same area as the pit, we would obtain a value of 29% of the area changed by one windthrow event. It is rather a high value if we consider that the reported percentage of the surface area covered by pits and mounds of different age reaches 14.3% (Šamonil *et al.* 2009), 32–53% (Borman *et al.* 1995) or 65% (Kabrick *et al.* 1997). Values similar to ours were presented for the Tatra Mountains by Rojan (2012), where the maximum proportion of the area occupied by pits and mounds (a result of one windthrow event) within one of the research polygons amounts to 20.1%. This shows that the windthrow process may have significant consequences on a local scale, and that locally a high percentage of the area covered by microtopography may be the result of one windthrow event.

Many authors also pointed out that trees more frequently occupy mounds than pits, or undisturbed areas (Denny and Goodlett 1956; Lyford and McLean 1966; Kabrick *et al.* 1997; Šebkova *et al.* 2012). Šebkova *et al.* (2012) assumed that mounds could have a higher probability of further damage than other areas. Also, Phillips and Marion (2005, 2006) pointed out the presence of "tree rich patches" within a forest stand, which are more frequently occupied by trees and are subject to further damage. If so, sites with the high density of windthrows and the high proportion of changes may result in a similar magnitude of damage in the next windthrow event. However, for the spruce which dominated the study area, the trend of more frequently occupying mounds than pits or other sites was shown not to be significant (Šebkova *et al.* 2012). Moreover, the planting of new trees was conducted within the area. Therefore, it is hard to indicate whether this relationship would occur in the study area.

Slope steepness

Our results show that slope inclination had weakly influenced some of the effects of the uprooting event. From all pit dimensions, the average pit depth and the average width to length ratio show significant changes connected with the slope gradient. A decrease in the average width to length ratio along with increasing slope inclination was



Sheffe test (A)

	<18	18-20	21-23	24-26	27-29	30-32	33-35	36-38	>38
<18									
18-20									
21-23									
24-26									
27-29									
30-32									
33-35									
36-38					0.038				
>38									

Sheffe test (B)

	<18	18-20	21-23	24-26	27-29	30-32	33-35	36-38	>38
<18									
18-20									
21-23									
24-26									
27-29									
30-32									
33-35									
36-38									
>38		0.007	0.008	0.002	0.034	0.036			

Sheffe test (C)

	<18	18-20	21-23	24-26	27-29	30-32	33-35	36-38	>38
<18									
18-20									
21-23									
24-26									
27-29									
30-32									
33-35									
36-38			0.024	0.001	0.001				
>38		0.037	0.006	0.0002	0.0005	0.042			

Fig. 8. Differentiation of the average windthrow pit length, depth and the width to length ratio in relation to slope inclination (a, b, c). Results of the Sheffé test showing statistically significant differences between slope inclination groups (d).

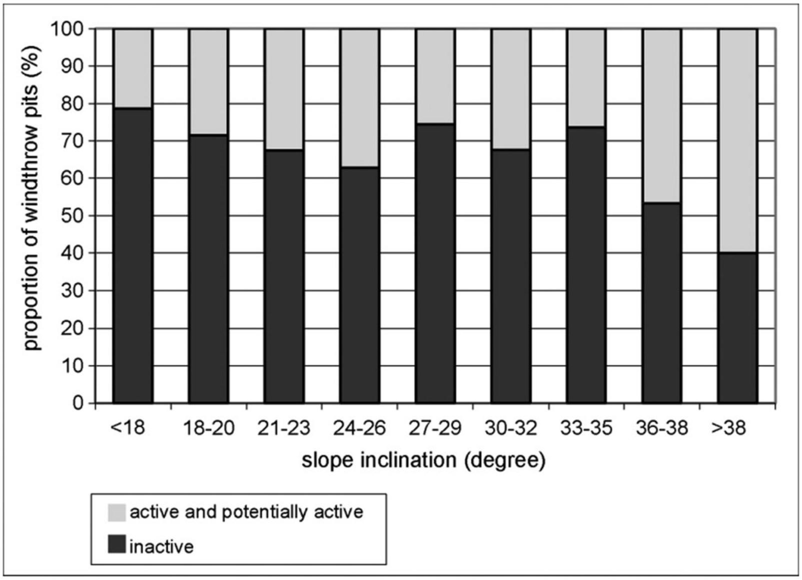


Fig. 9. Ratio of active and potentially active to inactive windthrow pits on different slope inclinations.

also noted by Gallaway *et al.* (2009), who linked it with the asymmetrical root system development within steep slopes. However, they noted an increase in every windthrow dimension (width, length, depth) along with slope inclination, which did not occur in our study area.

Clinton and Baker (2000) found that tree biomass did not significantly influence pit depth and mound thickness. They supposed that the depth of a pit was influenced by edaphic conditions, rather than by the size of a tree. However, their results were based on deciduous trees. The results of Phillips *et al.* (2015) showed more pronounced relationships between the tree size and rooting depth for pine and oak. However, they also suggested that rooting depth was, in many cases, not influenced by tree size. In our study area, a decrease in the pit depth along with increasing slope inclination may be connected with the shallower rooting within steep slopes, where the soil mantle is thinner.

Also, the ratio of active and potentially active to inactive windthrow pits, which expresses the

Table 5. Characteristics of windthrows in different study sites

Mean volume (m^3)	Mean area (m^2)	Volume of material (m^3 ha^{-1})	Layer of disturbed soil mantle (cm)	Area disturbed by one windthrow event (%)	Number of windthrows per ha (n ha^{-1})	Study area (author)
2.41	5.47	172.4	1.7	3.9	72	This study[a]
1.5	–	663.2	6.6	–	522	The Tatra Mts (Kotarba 1970, changed[c])[b]
1.88	–	–	3	–	230	The Tatra Mts (Dąbrowska 2009)[b]
1.66	2.58	882	6.6	8.2	384	The Tatra Mts (Rojan 2010)[b]
4[b]	–	95[b]	–	0.09[a]	–	The Sudety Mts (Pawlik 2013)[a b]
0.3	0.86	11.7	–	–	–	Puerto Rico Island (Lenart *et al.* 2010)[a]
1.32	1.59	205	2.4	2.5	155	The Ouachita Mts (Phillips *et al.* 2015)[b]

[a] Pit dimensions.

[b] Root plate dimensions.

[c] According to Norman *et al.* (1995), the values obtained by Kotarba (1970) are twofold too large, therefore all of them were divided by two.

amount of vegetation within pits, is partly related to slope inclination. This is consistent with the results of Gerber *et al.* (2002), which show a slight increase in the unvegetated surface area with increasing slope inclination for a windthrow site in the Swiss Alps.

The activity of slope processes

Many studies point out a significant increase in the shallow landslide frequency in logged areas (Jakob 2000; Sidle 2008). It could be expected that windthrow sites would also present an increase in landsliding in terms of the destroyed forest cover. Moreover, windthrow sites subject to salvage logging (similar to our study site) were shown by Gerber *et al.* (2002) to be more susceptible to landsliding than sites with no human activity. Within our study site we observed only two small, newly created landslides, which cover 0.003% of the whole study area. However, research was conducted 1.5 years after the event so, in the following years, new landslides may occur, therefore this issue needs further monitoring.

Hancock *et al.* (2011) noted no significant changes in the shape and size of the pits, no signs of gully erosion initiation, and no evidence of downslope sediment movement during the 3 years of monitoring. In our study area, only five of the investigated pits presented changes in their relief, caused by micro-scale landsliding or periodic spring activity. To our knowledge, no cases of springs created by uprooting were noted, so it may be that our observation is rather an exception. However, attention should be paid to this issue in the studies concerning the geomorphic consequences of uprooting. Also, monitoring is planned to check whether the periodic springs will be active in the next years because, if so, their activity may lead to some further geomorphic consequences, for example gully erosion.

Valuable information is provided by the observations of many windthrows created in the vicinity of a channel. Both windthrow pits and root plates deliver the soil material from the slopes directly into channels (Fig. 5). This fact shows that after a windthrow event slope–channel coupling may be facilitated. Apart from this, there is still the question of whether pit surfaces located in a higher topographic position cause an increase in slope wash activity. Hancock *et al.* (2011) and Pawlik (2012) reported no increase in the slope wash activity in the windthrow sites. Moreover, windthrow pits are assumed to play the role of a sediment trap within a hillslope (Gallaway *et al.* 2009; Pawlik *et al.* 2013), which can be partly confirmed by observations of water accumulating within them (Kabrick *et al.* 1997; Lyford and MacLean 1966). However, our results show a decrease in the average pit depth, a dimension which mostly contributes to the significance of a pit in sediment storage, at the highest slope inclinations. Also, the number of potentially active (mostly unvegetated) pits increases with slope inclination. Therefore, it may be the case that on slopes with a high inclination loose material from the pit can be subject to slope wash. This would require further research on the influence of slope inclination on the rooting habit, and the ability of slope wash to transport the material out of the pit.

Human impact

Human impact is yet another factor which also influences the magnitude of changes within a hillslope after a windthrow event. We do not have the data concerning the percentage of vegetation within each pit, however we can assume that all of them were initially 100% unvegetated. Thus, if we sum the surface area of all windthrow pits (3.9% of study site II) and the surface area without vegetation created by human impact (0.9% of study site II; Table 3), it appears that 18.4% of the whole unvegetated surface was created by salvage logging and planting. It is also worth noting that human activity can influence further root plate disintegration and deposition of loose material. Phillips *et al.* (2008, 2015) pointed out that cutting off tree trunks often caused root plates to fall back into the pit. In our study area, we did not observe such a situation. Moreover, if the trunk is cut off, the angle between the root plate plane and the downslope surface is diminished. In this manner, the slope inclination above which most of the root plate material falls beyond the pit (47° according to Norman *et al.* 1995) can be lower in such a situation.

Conclusions

The results of our study show the geomorphological impact of a severe windthrow event on the mountain landscape. Apart from increasing terrain roughness, uprooting can change the relief of small landforms, especially shallow landslides and lateral undercuts.

The quantified effects of tree uprooting shown in our study are similar to those obtained from other studies presenting the consequences of one windthrow event. Locally, however, the magnitude of changes varies significantly, and sites with a relatively high disturbance rate (14.5% of the area affected only by pits) can be distinguished.

The effects of uprooting are weakly controlled by slope inclination. The most pronounced relation occurs on steeply inclined slopes (>38°), within which the pits with the lowest average depths are located. Steep slopes also have a higher proportion of mostly unvegetated pits, which can suggest that an increase in slope wash activity is more likely to occur within steep slopes. Moreover, soil material from the slopes is delivered directly to the channels by numerous instances of windthrows created in the vicinity of a channel. Our research also provided evidence of periodic spring activity within windthrow pits, not observed in other studies. To answer the question of how a windthrow event affects the activity of slope processes more comprehensively, further research is needed based on windthrow site monitoring. Steep slopes in particular should be taken into consideration, as they might present different effects of uprooting.

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Dariusz Strzyżowski, Mirosław Żelazny Institute of Geography and Spatial Management, Jagiellonian University, Gronostajowa 7, 30–387 Cracow, Poland
E-mail: dariusz.strzyzowski@uj.edu.pl, miroslaw.zelazny@uj.edu.pl

Joanna Fidelus, Institute of Geography, Pedagogical University, Podchorążych 2, 30–084 Cracow, Poland
E-mail: jfidelus@up.krakow.pl

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