DE GRUYTER
OPEN

STUDIA GEOMORPHOLOGICA CARPATHO-BALCANICA
Vol. XLVIII, 2014: 17–34 PL ISSN 0081-6434

DOI 10.1515/sgcb-2015-0002

ŁUKASZ PAWLIK (KRAKÓW)

BIOGENIC IMPRINT ON HILLSLOPES IN THE SUDETY MTS. — ORIGIN AND CONSEQUENCES OF THE TREE UPROOTING PROCESS

Abstract. The main subject of this article is the tree uprooting process and its effects on forested hillslopes in the Sudety Mts. The research has been carried out between 2010 and 2012 in the Karkonosze National Park (KNP), Stołowe Mountains National Park (SMNP) and Suche Mts. The methods included: detailed geomorphological mapping and measurements of root plates of recently fallen trees and relict treethrow mounds and pits (called pit-and-mound microtopography), their qualitative description and measurements of diameter at breast height (dbh) of uprooted tree trunks.
The mean root plate volume was 0.3–1.4 m^3 in the KNP, 2.4–4.0 m^3 in the Suche Mts. and 0.6 m^3 in the SMNP. The mean treethrow mound volume was almost equal in the two selected study sites, ca. 1.6 m^3, the SMNP and Suche Mts. The research revealed a mosaic of forms that can be directly attributed to tree uprooting: created after deposition of root plates (various accumulation forms below them) or following their subsequent degradation e.g. gravel armours on rain washed treethrow mound surfaces, rock fragment veneers consisting of coarse fragments of regolith and bedrock. In the latter case, because tree root systems frequently penetrated regolith and fractured bedrock they were able to uplift ('mine') larger clasts during tree uprooting. The mean longest edge of such rock fragments was 16 cm in the Suche Mts., 26 cm in the SMNP and 33–56 cm in the KNP.
It has been shown that tree uprooting can contribute to the evolution of regolith and soils and it is an important factor of their disturbances. This reflects results from other sites in the World. However, in the Sudety Mts. the significance of tree uprooting has been validated only locally and it is suggested that its importance decreases proportionally to the area under consideration. Here, biogenic transport is limited to treethrow pits on gentle hillslopes but can be much more effective at steeper sites.

Key words: tree uprooting, pit-and-mound microrelief, biomechanical weathering, geomorphological mapping, Sudety

In memory of Professor Tadeusz Gerlach
(1932–2014)

INTRODUCTION

45 and 35 years have already passed since publication of two very intriguing and still influential papers. The first one, entitled *'Report on the origin of small earth hillocks on the Hala Długa in the Gorce range'* (G e r l a c h 1960), appeared

in the Polish Geographical Review as a novel interpretation of the origin of so called *hummocky meadow*, an assemblage of pit-mound forms at Hala Długa, Gorce Mts., southern Poland, that could have been caused by wind-toppled trees. The second paper was published under the title *'The morphogenetic role of foehn wind in the Tatra Mts.'* (Kotarba 1970) in the 4th issue of the *Studia Geomorphologica Carpatho-Balcanica* and focused on recent forms of uprooted trees. It could be said that through both papers Polish geomorphologists made an initial step towards *terra incognita* of biomorphodynamics of hillslopes disturbed by the process of tree uprooting.

Does trees contribute to sediment transport and hillslope morphology? That could have been a question behind both authors' novel, as it was that time, methodological approach and conceptual visions. The main aim of the articles was to describe and evaluate geomorphic impact and consequences of hurricane wind on hillslope morphology (but not as an aeolian set of processes). Two hidden assumptions entered the stage during this studies: forested hillslopes might have not been entirely static geoecosystems (what was frequently formulated *a priori*), and trees could contribute to downslope sediment transport. Although very influential abroad (e.g. Norman et al. 1995), the paper by A. Kotarba (1970) and the set of methods applied there have gained much more attention between Polish geomorphologists only recently (Dąbrowska 2009; Rojan 2010; Pawlik 2013c).

The forest belts in the Sudety Mts. were commonly thought to be a stable geoecosystem, without a major activity of morphogenetic processes. They supposed to play rather a role of accumulation zone, but not acting as a source area of sediments itself (e.g. Jahn 1989; Bieroński et al. 1992; Migoń 2008). However, hitherto observations of the tree uprooting process often suggest something different and that allow us to consider different scenarios of hillslope evolution and its morphodynamics under biotic factors, mainly trees. Its effects on soils and ecological processes in forests have been already under intensive research in the North America and Europe (Schaetzl et al. 1989a, b; Šamonil et al. 2009, 2010a). Although, the number of geomorphic studies on the tree uprooting process increased considerably in the recent years many forest ecosystems have not been analysed from the viewpoint of disturbances caused by fallen trees (Embleton-Hamann 2004; Phillips et al. 2008a, b; Gallaway et al. 2009; Gabet, Mudd 2010; Constantine et al. 2012; Pawlik 2013a). This is also true in case of the Sudety Mts. where between many variables having a potential effect on tree uprooting intensity and frequency, here one additional factor seems to have great influence on the process, that is changes in forest ecosystems caused by human activity (its spatial extent, species structure and health condition).

The aim of this paper is to present a synthesis and main results of studies that have been a part of the PhD project focused on the process of tree uprooting, its roles and consequences on geomorphic system of forested hillslopes in the Sudety Mts.

TREE UPROOTING — THEORETICAL BACKGROUND

Trees have an important ability to remodelled hillslope relief during the process of tree uprooting because their roots anchor firmly to the ground and bound soil-weathering material (sometimes weakly weathered and/or fractured bedrock) in root systems. After tree is uprooted it is an initial point in time when several subsequent degradation processes can commence i.e. erosion, soil creep, small-scale gravitational movements acting on soil material building an exposed root plate. As a result of detailed but still not numerous field studies tree uprooting has been recognized as an important process leading to hillslope microrelief formation (e.g. Norman et al. 1995, Embleton-Hamann 2004) and physicochemical changes in regolith and soils (e.g. Phillips, Marion 2005, 2006). So far soil analyses (Lutz 1940; Šamonil et al. 2010a, b) and *disturbance ecology* studies (Naka 1982; Šamonil et al. 2009) have made the greatest contribution to the essence of the process under consideration in the present paper.

The mechanism of tree uprooting was put in neat words as early as in the end of the 19th century (Shaler 1891; p. 273): *"When a forest is overturned by a strong wind the trees (…) are commonly torn from the ground or uprooted, and thus it occurs that the soil about the base of the bole is rended away so that it lies at right angles to its original position"*. However, overturning of trees and upheaval of their root systems can be an effect of several other natural processes not only by the impact of hurricane wind (Faliński 1986; Schaetzl et al. 1989a, b; Mitchell 2012) but, for instance, also by: 1) overloading by snow and ice (e.g. during ice-storms), 2) volcanic activity (e.g. eruption of the St. Helen volcano, USA, in 1980; Turner et al. 1997), 3) snow avalanches, 4) debris flows, *etc*.

Another factor is wind force necessary for uprooting a tree that is primary up to synoptic circumstances but also depends on trees' health condition, regional and local configuration of topography and soil-regolith features. The significance of these variables decrease along with increase in wind velocity. It is thought, however, that no tree can sustain an impact of wind blowing with speed over 29 ms^{-1} (Capecki 1971). Most frequently biotic and abiotic environmental agents strengthen each other, simultaneously or in time sequence one after another, what lead to faster decay of forests. Factors influencing uprooting of trees by wind impact can be as follows: 1) type of root system (its architecture, rooting depth), 2) wind speed, gustiness and direction, 3) soil thickness and wetness, 4) ground water level, 5) rainfall conditions before or during windstorm (soil saturation leads to decrease in soil cohesion), 6) size, shape and crown symmetry, 7) trunk properties (diameter at breast height, tree trunk height), 8) proportion of tree trunk to its crown (Bzowski, Dziewolski 1973), 9) wood properties (density, elasticity) (Schaetzl et al. 1989b).

A direct imprint of tree uprooting, well visible in natural but rare in managed forests, is distinct pit-and-mound microrelief. It is a unique trace of biological activity on the Earth's surface (Gabet, Mudd 2010). Due to degradation of soil material attached to a root system of fallen tree (root plate) and slow decomposition of roots and stem after a few decades treethrow mound is formed next to adjacent pit (a place formerly occupied by tree that was uprooted) (Fig. 1). It can take relatively short period of time in Michigan, USA, that is around 5–10 years (Schaetzl, Follmer 1990) but even 50–60 years in the Outer Western Carpathians, Czech Republic (Šamonil et al. 2009). The latter is the maximum time needed for complete decomposition of wood of fallen beech (*F. sylvatica*). The mean size of treethrow mounds vary largely between geographical regions from 0.2 m^3 in the New York state, USA up to 3.0 m^3 in forest of the Mazandaran province, Iran (Denny, Goodlett 1968; Kooch et al. 2012). However there is a clear relationship between climate zone and rates of treethrow mounds and root plates denudation. In the humid climate zone with a high annual rainfall level treethrow pits are very quickly filled with soil and organic matter and mounds levelled by erosional processes and creep. Infilling of pits can be as fast as 8 cm yr^{-1} in the tropical forest of Panama (Putz 1983), but only 6 mm yr^{-1} in the Karkonosze Mts., SW Poland (Parzóch 2001).

STUDY AREA

The present study has been conducted on the Polish side of the Sudety Mts., SW Poland. The research sites included: Karkonosze National Park (KNP), Stołowe Mountsins National Park (SMNP) and Suche Mts. (Fig. 2, Tab. 1). The choice of forest stands within the national parks allowed, at least partially, analyses of quasi-natural forests (e.g. *Zbocze* and *Łomniczka* research sites in the KNP). Studies in the Suche Mts. were motivated by the fact that this area belongs to the most severely damaged part of the Polish Sudety during the winter storm called Kyrill in 2007. This hurricane wind event allowed geomorphological

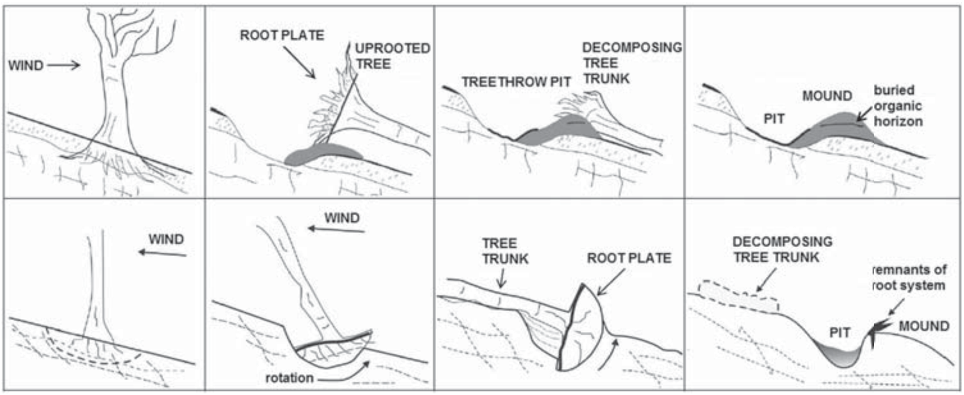

Fig. 1. Two sequences of the treethrow pit and mound formation showing tree uprooting along downslope vector (upper sequence) and upslope vector (lower sequence). When tree is uprooted upslope it does not result in organic matter burial in the treethrow mound (Author's own figure, based on Ł. Pawlik 2013a, b; modified)

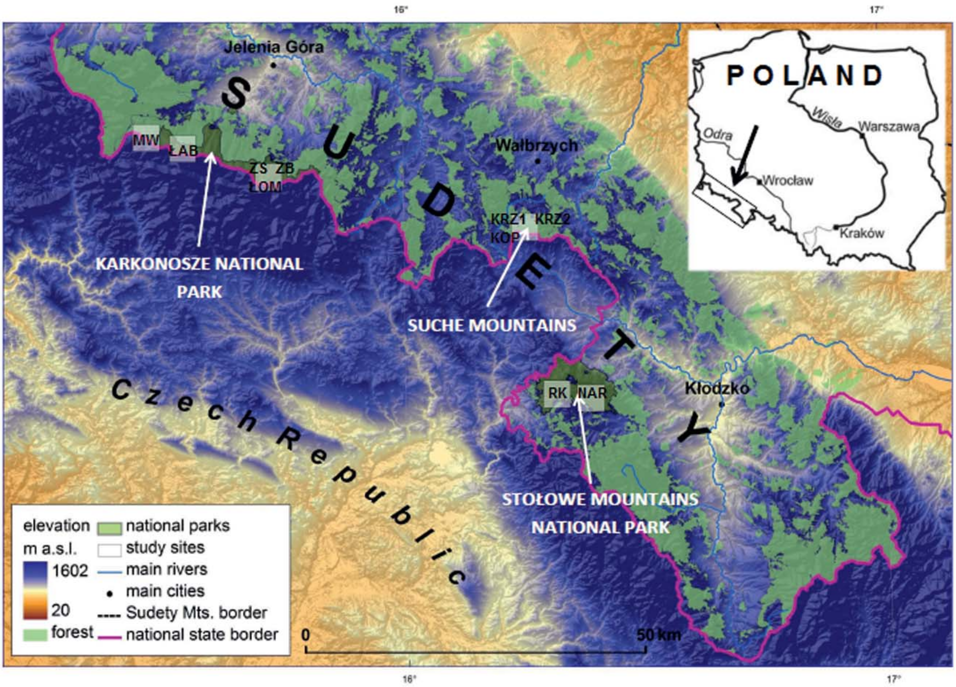

Fig. 2. Study area. Abbreviations: Karkonosze National Park: MW — *Mumlawski Wierch*, ŁAB — *Pod Łabskim Szczytem*, ZS — *Złoty Stok*, ZB — *Zbocze*, ŁOM — Dolina *Łomniczki*; Suche Mountsins: KRZ1 — *Krzywucha 1*, KRZ2 — *Krzywucha 2*, KOP — *Kopica*; Stołowe Mountains National Park: RK — *Rogowa Kopa*, NAR — *Narożnik*

mapping and measurements within relatively recent windthrow area with freshly exposed root plates (Pawlik 2012).

The research sites in the Stołowe and Suche Mts. belong to the lower forest belt. Only in the KNP field works were curried on within the upper forest belt (Sudetic montane spruce forest). In most cases of individual windthrows Norway spruce (*P. abies*) prevailed. Some limited number of uprooted beeches, Scots pines (*P. sylvestris* L.) and larches (*Larix Mill.*) were recorded in SMNP and Suche Mts. Before human interference to the Sudetic forests they were characterized by clearly distinguishable vegetation belts. However, later since the Middle Ages, the submontane (<500 m a.s.l.) and lower belt (500–1000 m a.s.l.) were partly deforested and since the 18^{th} century many areas were clear-cut and re-planted by Norway spruce monocultures. Such forest stands were more sensitive to the impact of natural disturbances both abiotic (strong winds, very high/low temperatures) and biotic (e.g. insect outbreaks). In the recent decades, in 1980s and 1990s in the entire Sudety Mts., but especially in their western part, large-scale trees mortality occurred due to industrial air pollutants (Mazurski 2008). Also because of this factor trees susceptibility to wind induced damage increased.

The field works were conducted on hillslopes mantled by different soil-weathering material related to the main rock types and local relief. The main types of rocks included granites (KNP), sandstones and mudstones (SMNP), rhyolites, rhyolitic tuffs and trachyandesites (Suche Mts.) (Tab. 1). Besides local geology conditions also regional relief and hillslope topography varied among the research sites: from almost flat plateau surfaces in the Stołowe Mts. to very steep hillslopes with slope inclinations up to 40° in the Suche Mts.

The climate of the Sudety is strictly linked to its elevation above the sea level (up to 1602 m) and its geographical orientation against prevailing air masses (especially for such meteorological variables as wind speed and direction). In the KNP the mean annual air temperature at Szrenica (1362 m a.s.l.) is 2° (1961–1990), the mean annual atmospheric precipitation is 1422 mm and the mean annual wind speed is 9.5 ms^{-1}. A higher value of the mean wind speed was recorded at Śnieżka (1602 m a.s.l.) 12.5 ms^{-1} (Sobik, Błaś 2008). And at this summit the frequency of very strong wind (> 15 ms^{-1}) is 34% per annum (Głowicki et al. 2005). In the entire Sudety Mts. prevailing wind directions are from W and NW (Fig. 3).

Table 1

The main attributes of the research sites in the Polish Sudety Mts.

Area	Study site	Altitude (m a.s.l.)	Mean slope angle (°)	Local relief form	Geology (age)	Dominant tree species (mean age in years)
KNP	Złoty Stok	1070–1140	22	hillslope	granite (Carboniferous)	*P. abies* (89–114)
	Zbocze	1170–1190	22	hillslope		*P. abies* (174–194)
	Łomniczka	1100–1180	25	steep valley side		*P. abies* (154)
	Łabski Szczyt	1130–1160	10	hillslope		*P. abies* (22)
	Mumlawski Wierch	1150–1200	10	gently inclined summit		*P. abies* (32 and 164)
SMNP	Rogowa Kopa	660–760	25	steep hillslope	mudstone (Cratecaous)	*F. sylvatica* (70)
	Narożnik	780–760	5	flat summit plateau	sandstone (Cratecaous)	*P. abies* (75)
Suche Mts.	Kopica	700–786	25	hillslopes and summit	rhyolitic tuff (Perm)	*P. abies* (45 and 115)
	Krzywucha 1	620–700	15	hillslope	trachyandesite (Perm)	*F. sylvatica* (100)
	Krzywucha 2	710–791	15	hillslope		*F. sylvatica* (45)

RESEARCH METHODS

The study was conducted by detailed geomorphological mapping and measurements with the use of: a laser target marker (LTM TruePulse 200), handheld GPR receiver (Garmin GPSMap 62), geological compass and measuring tape. The aim of the mapping was to show in details a geomorphic variability of hillslope surfaces through the measurement of the height of treethrow mounds and the depth of treethrow pits what allow calculation of the soil-weathering material volume uplifted with each root system. A similar approach was used during the measurements

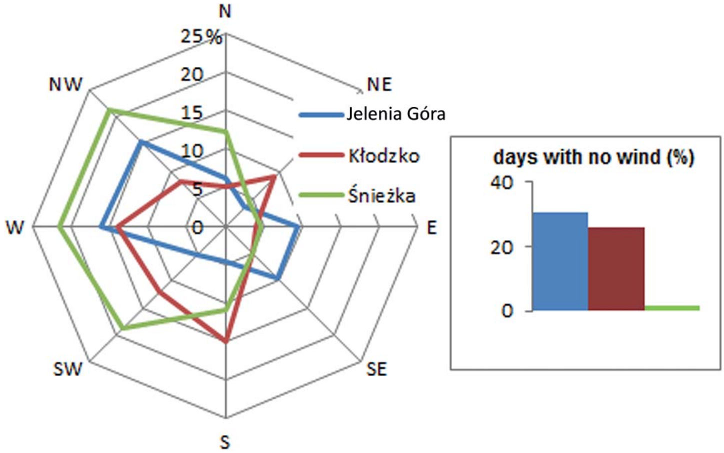

Fig. 3. A radar diagram with prevailing wind directions at the chosen Sudetic meteorological stations (Głowicki 2005; Głowicki et al. 2005). All data for the time span 1971–2000

of root plates. During the mapping several qualitative features were also recorded and between them for instance: degree of vegetation cover of root plates, mounds and pits, size of extricated coarse rock fragments, diameter at breast height and azimuths of fallen tree trunks. For the calculation of the treethrow mound, pit and root plate volumes a formula for half ellipsoid with three unequal axes was used (Kotarba 1970; Norman et al. 1995; Dąbrowska 2009; Pawlik 2013a) (Fig. 4).

RESULTS

UPROOTED TREES AND WINDTHROW AREAS

In the Sudety Mts. the most recent and the largest windthrow areas are those caused by the Kyrill windstorm that hit the European forests in January 2007. The strong wind event brought serious disturbances along the entire Polish part of the Sudety massif with the highest damage reported from its middle and western part (Pawlik 2012). In the Karkonosze National Park and Suche Mts. research sites were established within hillslope segments with the forest disturbed by the abovementioned winter storm (that is *Złoty Stok*, *Zbocze*, *Kopica* and *Krzywucha 1*).

In the KNP the mean volume of root plates range from 0.3 to 1.4 m^3 (Tab. 2). It depends on the time of their exposition but also tree size given here as a diameter at breast height (dbh). The root plates with the largest dimensions were not so strongly deteriorated as those from *Pod Łabskim Szczytem* and *Mumlawski*

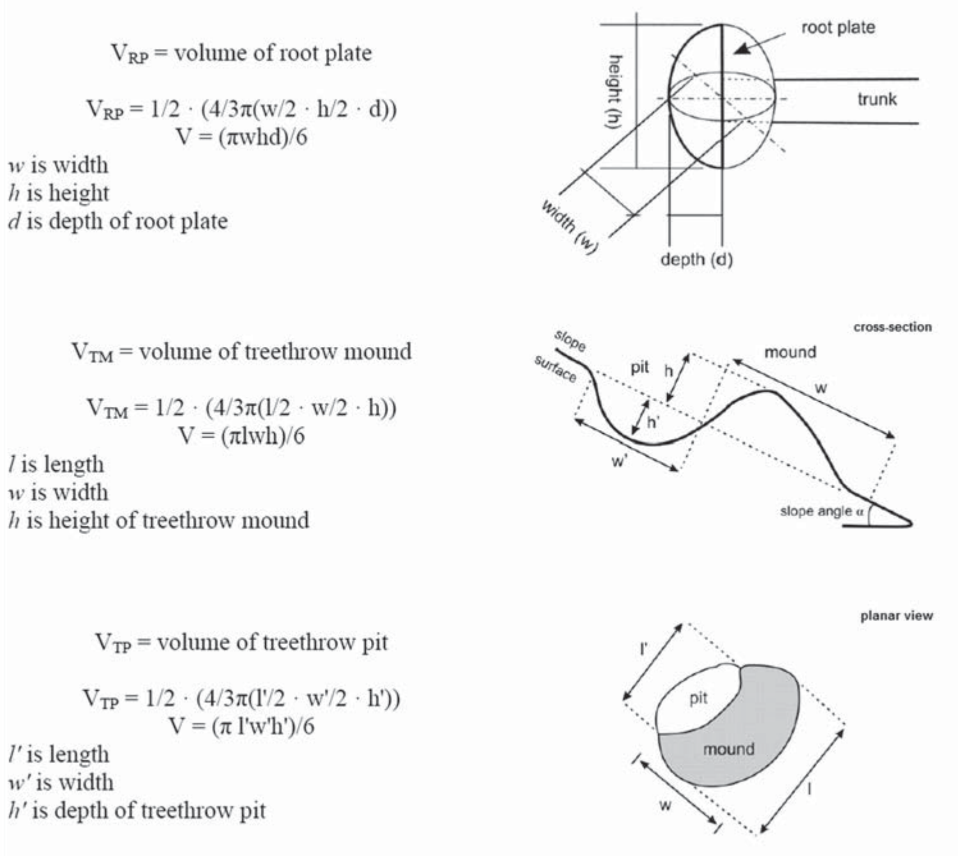

Fig. 4. The method of treethrow mounds, pits and root plates volume calculation (Kotarba 1970; Norman et al. 1995; Dąbrowska 2009; Pawlik 2013a)

Wierch. But for instance trees at the *Pod Łabskim Szczytem* site were damaged during a catastrophic foehn wind event that took place in 1966 (Kwiatkowski 1969; Pawlik 2013b). Whereas in the other study sites, except of *Mumlawski Wierch* where forest decay were caused mainly by industrial pollutants, forest damage was an effect of strong wind attributed to much recent events. Smaller mean root plate volume at *Złoty Stok* can be associated with younger uprooted trees (smaller dbh, see Tab. 1 and 2).

Taking into account all the study sites from the Sudety Mts. a very strong relationship has been found between the mean root plate volume and the mean diameter at breast height with coefficient of determination $R^2 = 0.9$ (Fig. 5). This is nonlinear relationships with the best fitted exponential regression line. In this case only research sites with recently uprooted trees have been considered.

In all places root plates consisted coarser fragments of regolith and bedrock. The largest mean dimensions of rock fragments were measured at the *Łomniczka* site, but extremely large boulder of granite, 185 cm in length, was measured in the

Table 2

Main results of the field studies conducted in the Polish Sudety Mts.

Area	Research site	Number of measured forms	root plate volume	mound volume	pit volume	dbh
			m³			cm
KNP	Zbocze	53	1.1	–	–	38
	Pod Łabskim Szczytem	14	0.3	–	–	34
	Złoty Stok	43	0.5	–	–	21
	Łomniczka	46	1.4	–	–	36
	Mumlawski Wierch*	12	0.4	0.5	–	32
SMNP	Rogowa Kopa	83 mounds 82 pits	–	1.7	1.6	–
	Narożnik	25	0.6	–	–	26
Suche Mts.	Kopica	149	4.0	–	–	–
	Krzywucha 1	22	2.4	–	–	43
	Krzywucha 2	23 pit–mound forms	–	1.5	1.5	–

* Only at this study sites the measurements were carried out through a longitudinal hillslope transect due to small amount of recorded forms.

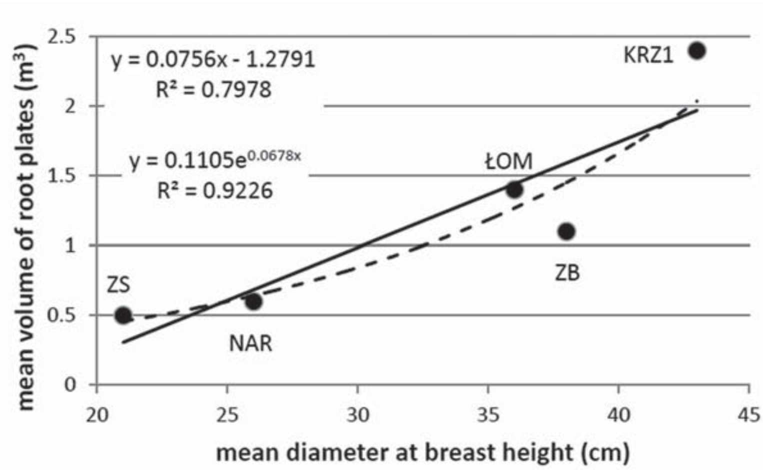

Fig. 5. Relationship between diameter at breast height of uprooted tree trunks and volume of their root plates as shown by linear and exponential regression lines. Only trees with approximately similar time of uprooting have been shown (origin, the figure not previously published). Abbreviations: see figure 2

root plate mapped at *Zbocze* (Fig. 6). A larger fragment (200 cm) was found in the treethrow pit at *Zbocze* too, but it was not a subject of transport during uprooting.

It is evident that more favourable conditions within the lower forest belt allowed trees and their root systems to reach larger dimensions, even at the steepest sites. This is reflected in the mean volumes of root plates recorded in the Suche and Stołowe Mts. (Tab. 2). But the lower mean volume of root plates at *Narożnik* was predominantly an effect of its low thickness (only *ca.* 20 cm). Here,

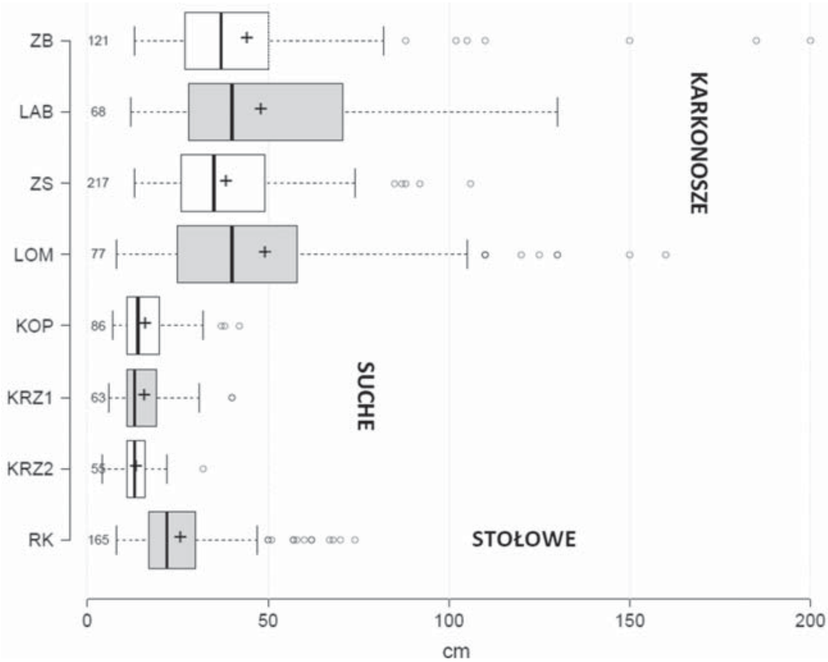

Fig. 6. Box-plots showing variability in rock fragment sizes at each study site. Only dimension of the longest edge of each measured clast has been shown. RK and KRZ2 represents microsites with treethrow mounds and pits (pit-mounds microtopography). The rest study sites represents rock fragments from root plates, corresponding to them treethrow pits and accumulation forms (origin, this figure has not been published yet). This figure was made with *'BoxPlotR: a web-tool for generation of box plots'* (http://boxplot.tyerslab.com). The black vertical bar indicates median whereas the mean values are marked with crosses

on sandy and saturated ground (water was recorded in 68% of the pits) *P. abies* developed very broad and flat root systems.

Only in the Suche Mts., at *Kopica*, clear accumulation forms have been recorded. However, even on such small area they differed considerably between each other what is primary function of regolith properties between various segments of hillslopes. Here two parts were distinguished: 1) head of the valley with stream sources where slope covers are thicker and more chemically changed (weathered), and 2) steep northern hillslope with thin regolith layer consisting mainly rock particles of coarser fractions (gravel and cobbles), with sharp edges

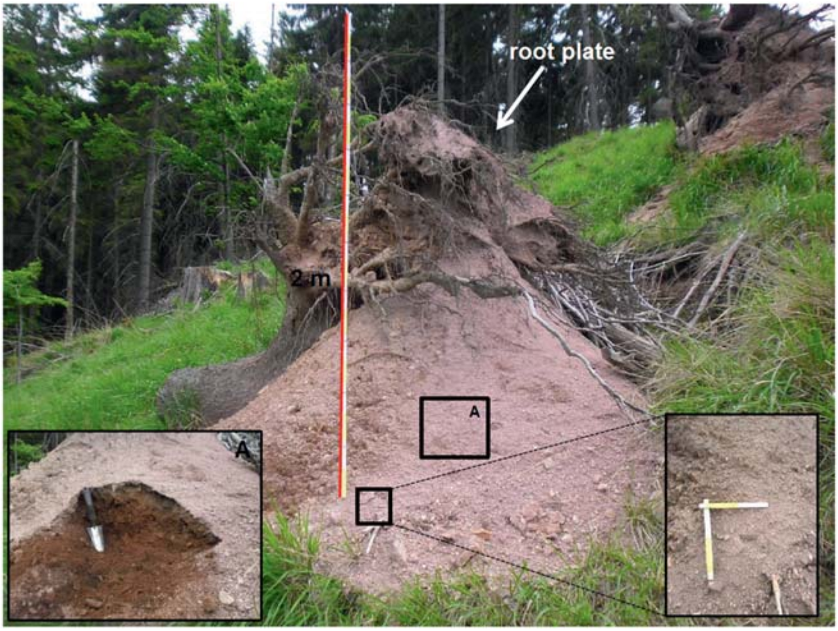

Fig. 7. The root plate of uprooted tree at the Kopica study site (its eastern side with deeper regolith cover), Suche Mts. The mineral material consisting of different particle fractions has been removed gravitationally from the root plate building cone-like form (Photo: Author, 2012).

and no traces of chemical alteration. Such properties allowed development of many accumulation forms with various properties (Fig. 7). Thicker root plates with more sandy material were recorded in the first distinguished part and thinner root plates with gravels and cobbles in the second one.

The measured azimuths of uprooted tree stems and stumps positively correspond with the main wind directions recorded at different meteorological stations across the Sudety (Fig. 2 and 8). However trees from other places did not

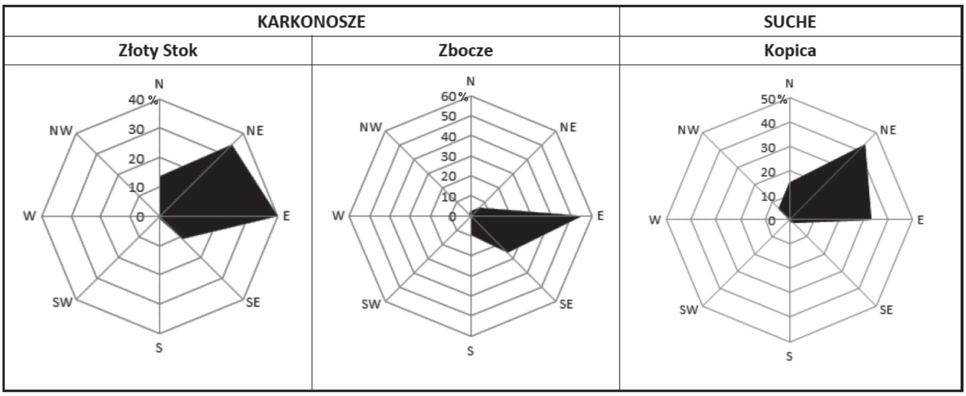

Fig. 8. Azimuths of the uprooted tree trunks and stumps (at *Kopica*) recorded in the Karkonosze and Suche Mts.

reflect similar relationships so clearly. This points to other variables that could have played a role in such redistributions of trees e.g. local topography or wind gusts from other directions.

PIT-AND-MOUND MICROTOPOGRAPHY

Pit-and-mound microtopography was mapped at only two study sites: *Rogowa Kopa* and *Krzywucha 2*. Much higher density of the pit-mound microsites, 40 per ha, was at *Rogowa Kopa* whereas at *Narożnik* only 10 forms per ha were recorded (Pawlik 2013b; Pawlik et al. 2013a, b). The latter was in young beech forest of the mean age ca. 50 years probably introduced there artificially. Because of such young age of the trees and no remnants of decomposing coarse woody debris of fallen trees presented, it is highly probable that the observed pit-mound topography had developed before introduction of the present forest (perhaps in the first part of the 20^{th} century or earlier). The forest floor was occupied by sparse understory vegetation and for this reason a thin blanket of rock fragments chaotically covering the hillslope surface was clearly visible. It is suggested that this feature might be an effect of tree uprooting because almost all treethrow mounds were covered by similar material.

On the south-western hillslope of *Rogowa Kopa* very well developed and prevent hummocky microtopography was documented that has been already interpreted as windthrow morphology (Migoń et al. 2011; Pawlik et al. 2013a, b). The forms of pit-mound microsites covered almost 5% of the research site. The mean volume of treethrow mounds was 1.7 and treethrow pits 1.6 m^3 (Tab. 2). The spatial orientation of both forms — pits and mounds — indicates that almost all trees were toppled downslope.

One of the most important features of the mapped forms is the presence of coarser clasts of mudstone on the mounds (Fig. 9). This feature was recorded in

Fig. 9. Examples of two microsites with coarse fragments of mudstones deposited on the treethrow mound (left) and excavated in the treethrow pit (right), *Rogowa Kopa*, Stołowe Mts. (Photos: Author). The black broken line indicates the upper edge of the treethrow pits.

57% and additionally in 7% of cases larger rock fragments were observed on edges and sides of the pits. The mean length of all clasts was 26 cm. This proves relatively high efficiency of root system in deep penetration of fractured bedrock and then extrication of large unweathered clasts in the process of tree uprooting. Additionally, the mounds' surfaces were washed by rain water what led to the formation of fine-gravel armour.

In almost all soil profiles made through pit-mounds microsites (along *w-w'* axes, see fig. 4) buried humus horizon and/or wood remnants of roots or trunk were found in the treethrow mounds and *ca.* 20–30 cm of accumulated organic matter in the pits (Pawlik 2013b; Pawlik et al. 2013b).

DISCUSSION

The effects of tree growth and mortality are well visible in the Sudety Mts. mainly due to the process of tree uprooting. In extreme cases trees colonize uncovered bare bedrock and when toppled some part of bedrock can be extricated in a root plate and deposited on hillslope surface (Phillips et al. 2008a, b). However, in case of deeply rooting trees (e.g. beech) or shallow regolith larger fragments of rocks can be uplifted as well. Such consequences were observed in most of the research sites: in the Stołowe Mts. on mudstones, Suche Mts. on rhyolitic tuffs and Karkonosze on granites. It is a strong argument after hypothesis saying that trees play a dominant role in a local soil thickening (Phillips et al. 2008a). They also act as an agent of uneven redistribution of soil material across a hillslope (Gabet, Mudd 2010). It is just evident if we take into account pit-and-mound microtopography. It is also an evidence of biotic transport, more often acting in downslope direction as trees are preferably toppled along this vector (Norman et al. 1995). Here, the *Rogowa Kopa* and *Krzywucha 2* study sites were a good example of it on very steep hillslopes. In case of gentle inclined surfaces soil-weathering material removed from a root plate mostly goes back to treethrow pit and it is only mixed within it. Mixing of soil material within treethrow mounds can be attributed to almost flat surfaces in the Stołowe Mts. (*Narożnik*) and gentle hillslopes in Karkonosze (*Złoty Stok, Zbocze*). In the KNP hillslope microtopography, not connected with tree uprooting, is highly differentiated with numerous niches and levelled segments of hillslope surface that do not allow further downslope transport of organo-mineral matter from root plates. Although, root plates reached high volumes quite frequently the material they consisted returned to treethrow pits or sometimes, as in the case of the *Pod Łabskim Szczytem* site, the coarsest fragments of bedrock have been halted in root systems for many decades (Fig. 10).

Simultaneously, it has been proved that tree uprooting contributes to Cambisols evolution (Šamonil et al. 2010a) and spatial heterogeneity of soils in microscale (Šamonil et al. 2010b). Much earlier reports from Michigan, USA, of R.J. Schaetzl (1986) indicated a possibility of soil profile inversion in treethrow

Fig. 10. Large boulders trapped in the root systems of uprooted trees at Pod Łabskim Szczytem, Karkonosze (both photos: Author, 2012). The length of the tape (right side photo) is 150 cm.

mounds. The author documented mixed soil horizons and almost undisturbed but inverted soil profile over untouched sequences of soil horizons. The forest fire that followed the uprooting event caused fast collapse of root plates (after complete burning of tree stems) and subsequent burial of upheaved soil horizons (Schaetzl 1986; Schaetzl, Follmer 1990). The same situation was documented at *Rogowa Kopa*, but probably with no forest fire engaged as a factor of almost immediate tree stems decomposition (Pawlik et al. 2013b). Fast degradation of root plates were observed in the Suche Mts. where after the Kyrill storm in 2007 all fallen trees on Mt. Czarnek (868 m a.s.l.), north of *Kopica*, were burnt due to fire in 2008 (Pawlik 2013c).

Some authors formulated a hypothesis that changes in soils caused by tree uprooting could be an alternative to probably overestimated role of frost processes (e.g. Lutz, Griswold 1939). This issue was described in several later publications (e.g. Gerlach 1960; Embleton-Hamann 2004). They consider the issue of natural disturbances of soil horizons in various ways and formation of stone structures like layers and armours (Small et al. 1990; Phillips, Lorz 2008; Pawlik et al. 2013a). The structures or rock fragment veneers of unknown age, but probably quite young, were observed at *Rogowa Kopa*, *Kopica* and *Krzywucha*. Generally, within the study sites rock-fragment veneers formed in two situations: 1) at disturbed and uncovered slope surfaces with upper soil horizons and regolith removed in places previously occupied by trees (treethrow pits), they were not a subject of downslope transport but only, in some cases, transport to vertical position in root plates and then returned to the pits due to gravitational processes (see Fig. 3, p. 50, Pawlik 2013d), 2) below accumulation forms and, in the case of relict forms, below treethrow mounds where they were a subject of soil weathering material redistribution removed from the root plates. It was suggested that tree uprooting is responsible for the development of rock fragment veneers on initial soils at steep localities and this surficial layer plays a protective role inhibiting water erosion (see also Osterkamp et al. 2006).

CONCLUSIONS

Tree uprooting is a biomechanical process connected with biological activity of trees and occurrence of natural disturbances that cause complex changes in forest stands. The process is directly linked with such phenomena as bioturbations, biomechanical weathering and biogenic transport. In favourable conditions it can lead to (at least): migration of the weathering front, mixing of soils and regolith, diffusive-like downslope redistribution of soil-weathering material.

Due to biogenic transport functions of tree uprooting in the temperate forest a microtopography of hillslopes can be remodelled and gained attributes of distinct pit-and-mound microrelief for decades or centuries before those microsites disappear completely through infilling of pits and flattening of mounds. Such uneven redistribution of soil-weathering material across a hillslope, both vertically and horizontally, has important effects on hydrological regime of the sites too. Treethrow pits plays a role of local water concentration sites with enhance leaching of soluble minerals. They are also places of large accumulation of organic matter from surrounding trees and area (up to 20–30 cm at *Rogowa Kopa*). Whereas treethrow mounds are sites of intensive rain splash and fast rainwater diffusion as evidenced by their rain-washed surfaces, they are frequently covered by a blanket of so called gravel armour.

Another good example of tree uprooting effects are large fragments of bedrock uplifted in root plates of fallen trees. Before a complete decomposition of tree wood such rock fragments are kept above the ground surface for many years. Because smaller fractions are removed from the root plate much faster, after decomposition of the root system, coarser clasts of regolith and bedrock start to form the upper horizons of soil mantles. In case of more recent events they can form specific hillslope stone pavements (rock fragment veneers) and their origin would be alternative to frequently accepted in such situations periglacial processes e.g. rock fragment upfreezing.

To sum up, in the Polish Sudety Mts. the evidence of the following forms attributed to tree uprooting has been recorded:

1. relict assemblages of treethrow mounds and pits forming distinct pit-and-mound microrelief;
2. recently uprooted trees and their remnants in various stages of decomposition and degradation;
3. rock fragment veneers and stone blankets built of coarse rock fragments detached from regolith and bedrock in root systems of fallen trees;
4. gravel armours, rain-washed and developed on surfaces of treethrow mounds;

5. accumulation structures below root plates (e.g. micro-cones) formed due to various gravitational processes and erosion.

ACKNOWLEDGES

I thank prof. Piotr Migoń (my PhD supervisor) for his help and suggestions on all stages of the field works. For help during the field campaigns I would like to thank: Teresa Pawlik, Anna Pokorny, Krzysztof Strug and Filip Duszyński. The studies were supported by the MNiSW research grant No NN306032940. The comments of Łukasz Longosz (Stanfords Ltd., London, U.K.) and two Reviewers are greatly acknowledged.

Institute of Geography, Pedagogical University of Cracow
ul. Podchorążych 2, 30-084 Kraków, Poland
lpawlik@up.krakow.pl

REFERENCES

Bieroński J., Chmal H., Czerwiński J., Klementowski J., Traczyk A., 1992. *The present-day denudation of the Karkonosze Mts.* [in:] *Denudational system of Poland.* A. Kotarba (ed.), Prace Geograficzne IGiPZ PAN 155, 151–169 (in Polish, with English summary).

Bzowski M., Dziewolski J., 1973. *Damage in the forests of the Tatra National Park caused by foehn wind (halny) in the spring of 1968.* Ochrona Przyrody 38, 115–153, (in Polish, with English summary).

Capecki Z., 1971. *Natural calamities in forest*. Sylwan 115, 2, 67–74, (in Polish, with English summary).

Constantine J.A., Schelhaas M.-J., Gabet E., Mudd S.M., 2012. *Limits of windthrow-driven hillslope sediment flux due to varying storm frequency and intensity.* Geomorphology 175–176, 66–73.

Dąbrowska K., 2009. *The morphogenetic impact of the bora type wind (19th November 2004) on the relief of Danielov dom area (The High Tatras).* Landform Analysis 11, 5–10.

Denny Ch.S., Goodlett J.C., 1968. *Tree-throw origin of patterned ground on beaches of the ancient Champlain Sea near Plattsburgh, New York.* U.S. Geological Survey Professional Paper 600-B, 157–164.

Embleton-Hamann C., 2004. *Processes responsible for the development of a pit and mound microrelief.* Catena 57, 175–188.

Faliński J.B., 1986. *Vegetation dynamics in temperate lowland primeval forests: ecological studies in Białowieża forest.* Dordrecht: W. Junk, 537 pp.

Gabet E.J., Mudd S.M., 2010. *Bedrock erosion by root fracture and tree throw: a coupled biogeomorphic model to explore the humped soil production function and the persistence of hillslope soils.* Journal of Geophysical Research 115, F04005, doi:10.1029/2009JF001526.

Gallaway J.M., Martin Y.E., Johnson E.A., 2009. *Sediment transport due to tree root throw: integrating tree population dynamics, wildfire and geomorphic response.* Earth Surface Processes and Landforms 34, 1255–1269.

Gerlach T., 1960. *Report on the origin of small earth hillocks on the Hala Długa in the Gorce range.* Przegląd Geograficzny, 32, 1–2, 86–93, (in Polish, with English summary).

Głowicki B., 2005. *The Karknosze Mts. Climate.* [in:] *Karkonosze. Przyroda nieożywiona i człowiek*. M. P. Mierzejewski (ed.), Wrocław University Press, Wrocław, 381–397, (in Polish).

Głowicki B., Otop I., Urban G., Tomczyński K., 2005, *Climate* [in:] *Opracowanie Ekofizjograficzne dla Województwa Dolnośląskiego.* Wojewódzkie Biuro Urbanistyczne, Wrocław, (in Polish).

Jahn A., 1989. *The soil creep on slopes in different altitudinal and ecological zones of Sudetes Mountains.* Geografiska Annaler, Series A., Physical Geography 71, 3/4, 161–170.

Kooch Y., Hosseini S.M., Mohammadi J., Hojjati S.M., 2012. *Effects of uprooting tree on herbaceous species diversity, woody species regeneration status and soil physical characteristics in a temperate mixed forest of Iran.* Journal of Forestry Research 23, 1, 81–86.

Kotarba A., 1970. *The morphogenetic role of foehn wind in the Tatra Mts.* Studia Geomorphologica Carpatho-Balcanica 4, 171–188.

Kwiatkowski J., 1969. *Windthrows on the northern slopes of the Karkonosze Mts. (4–5 November 1966) and their climatic origin.* Opera Corcontica 6, 25–33, (in Polish, with German summary).

Lutz H., 1940. *Disturbance of forest soil resulting from the uprooting of trees.* Yale University, School of Forestry, Bul. 45, USA, 37 pp.

Lutz H., Griswold F.S., 1939. *The influence of tree roots on soil morphology.* American Journal of Science 237, 389–400.

Mazurski K.R., 2008. *Destruction of forests in the Sudetes — thirty years later.* [in:] *Výroční konference ČGS*. Sborník příspěvků, Liberec, 25–29.08.2008, 30–41. Online 01.03.2011 — http://mazurski.eu/.

Migoń P., 2008. *Contemporary relief evolution of the Sudety Mts. and its Foreland.* [in:] *Współczesne przemiany rzeźby Polski*. L. Starkel, A. Kostrzewski, A. Kotarba, K. Krzemień (eds.), SGP, IGiGP UJ, IGiPZ PAN, Kraków, 135–163, (in Polish).

Migoń P., Latocha A., Parzóch K., Kasprzak M., Owczarek P., Witek M., Pawlik Ł., 2011. *Contemporary geomorphic system of the Stołowe Mountains.* [in:] *Geoekologiczne warunki środowiska przyrodniczego Parku Narodowego Gór Stołowych.* T. Chodak, C. Kabała, J. Kaszubkiewicz, P. Migoń, J. Wojewoda (eds.), WIND, Wrocław, Poland, 1–52, (in Polish with English abstract).

Mitchell S.J., 2012. *Wind as a natural disturbance agent in forests: a synthesis.* Forestry 86, 147–157.

Naka K., 1982. *Community dynamics of evergreen broadleaf forests in Southwestern Japan. I. Wind damaged trees and canopy gaps in an evergreen oak forest.* The Botanical Magazine Tokyo 95, 385–399.

Norman S.A., Schaetzl R.J., Small T.W., 1995. *Effects of slope angle on mass movement by tree uprooting.* Geomorphology 14, 19–27.

Osterkamp W.R., Toy T.J., Lenart M.T., 2006. *Development of partial rock veneers by root throw in a subalpine setting.* Earth Surfaces Processes and Landforms 31, 1–14.

Parzóch K., 2001. *Contemporary geomorphic processes in the Karkonosze Mts. under human impact*. Unpublished Phd thesis, Department of Geomorphology, Wrocław University, Poland, (in Polish).

Pawlik Ł., 2012. *Forest damage in the Sudety Mts. caused by the Kyrill storm (18–19.01.2007) — historic and regional implications.* Przegląd Geograficzny 84, 1, 53–75, (in Polish, with English summary).

Pawlik Ł., 2013a. *The role of trees in the geomorphic system of forested hillslopes — a review.* Earth-Science Reviews 126, 250–265.

Pawlik Ł., 2013b. *Tree uprooting as a factor in forested hillslope dynamics, from the example of the Polish part of the Sudety Mountains, SW Poland.* Unpublished Phd thesis, Department of Geomorphology, Wrocław University, Poland, (in Polish, with English summary).

Pawlik Ł., 2013c. *Remodelling of slope surface in the Suche Mts., SW Poland, as an effect of catastrophic windthrow caused by the Kyrill storm in 2007.* [in:] *Arbres & dynamiques*. A. Decaulne (ed.), Presses Universitaires Blaise Pascal, University of Clermont-Ferrand 2, France, 49–69.

Pawlik Ł., 2013d. *Tree uprooting process and its implications in biomechanical slope cover and slope microrelief disturbances in the upper forest zone of the Polish Karkonosze Mts.* Prace Geograficzne 135, 41–55, (in Polish, with English abstract).

Pawlik Ł., Migoń P., Owczarek P., Kacprzak A., 2013a. *Surface processes and interactions with forest vegetation on a steep mudstone slope, Stołowe Mountains, SW Poland.* Catena 109, 203–216.

Pawlik Ł., Kacprzak A., Musielok Ł., Bebak J., 2013b. *Distinct form of microrelief on steep slopes of the Rogowa Kopa, Stołowe Mts. — in the light of geomorphological and pedological evidence.* [in:] *Landscapes. Diversity, Ecology and Conservation.* P. Migoń, M. Kasprzak (eds.). Proceedings of the 3rd International Conference on Sandstone Landscapes, Kudowa-Zdrój (Poland), 25–28 April 2012, 132–138.

Phillips J.D., Marion D.A., 2005. *Biomechanical effects, lithological variations, and local pedodiversity in some forest soils of Arkansas*. Geoderma 124, 73–89.

Phillips J.D., Marion D.A., 2006. *The biomechanical effects of trees on soils and regoliths: beyond treethrow.* Annales of the Association of American Geographers 96, 233–24.

Phillips J.D., Lorz C., 2008. *Origins and implications of soil layering.* Earth-Science Reviews 89, 144–155.

Phillips J.D., Marion D.A., Turkington A.V., 2008a. *Pedologic and geomorphic impacts of a tornado blowdown event in a mixed pine-hardwood forest.* Catena 75, 278–287.

Phillips J.D., Turkington A.V., Marion D.A., 2008b. *Weathering and vegetation effects in early stages of soil formation.* Catena 72, 21–28.

Putz F.E., 1983. *Treefall pits and mounds, buried seeds, and the importance of soil disturbance to pioneer trees on Barro Colorado Island, Panama.* Ecology 64, 1069–1074.

Rojan E., 2010. *The role of severe windstorms in modifying the mountain forest floor relief: a case of the blowdown area in the Slovakian High Tatras*. Czasopismo Geograficzne 81, 103–123, (in Polish, with English summary).

Schaetzl R.J., 1986. *Complete soil profile inversion by tree uprooting.* Physical Geography 7, 2, 181–189.

Schaetzl R.J., Follmer L.R., 1990. *Longevity of treethrow microtopography: implications for mass wasting.* Geomorphology 3, 113–123.

Schaetzl R.J., Johnson D.L., Burns S.F., Small T.W., 1989a. *Tree uprooting: review of terminology, process, and environmental implications.* Canadian Journal of Forest Research 19, 1–11.

Schaetzl R.J., Burns S.F., Johnson D.L., Small T.W., 1989b. *Tree uprooting: review of impacts on forest ecology.* Vegetatio 79, 165–176.

Shaler N.S., 1891. *The origin and nature of soils.* [in:] *USGS 12th Annual report 1890–1891*. J.W. Powell (ed.), Government Printing Office, Washington, D.C., 213–245.

Small T.W., Schaetzl R.J., Brixie J.M., 1990. *Redistribution and mixing of soil gravels by tree uprooting.* Professional Geographer 42(4), 445–457.

Sobik M., Błaś M., 2008. *The significance of climate in functioning of the Karkonosze forest ecosystems.* [in:] *Monitoring ekosystemów leśnych w Karkonoskim Parku Narodowym*. A. Mazur, A. Raj, R. Knapik (eds.), Karkonosze National Park Press, Jelenia Góra, 17–28, (in Polish).

Šamonil P., Antolík L., Svoboda M., Adam D., 2009. *Dynamics of windthrow events in a natural fir-beech forest in the Carpathian mountains.* Forest Ecology and Management 257, 1148––1156.

Šamonil P., Tejnecký V., Borůvka L., Šebková B., Janík D., Šebek O., 2010a. *The role of tree uprooting in Cambisol development.* Geoderma 159, 83–98.

Šamonil P., Král K., Hort L., 2010b. *The role of tree uprooting in soil formation: A critical literature review.* Geoderma 157, 65–79.

Turner M.G., Dale V.H., Everham E.H., 1997. *Fires, hurricanes, and volcanoes: comparing large disturbances.* BioScience 47, 11, 758–768.