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Deciphering the history of forest disturbance and its effects on landforms and soils – lessons from a pit-and-mound locality at Rogowa Kopa, Sudetes, SW Poland

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Abstract. The historical dimension of pit-and-mound topography has been studied at the Mt Rogowa Kopa locality, Stołowe Mountains, SW Poland. This site represents one of the best developed regional examples of hummocky forest floor relief due to widespread tree uprooting and subsequent degradation of root plates. Through map analysis and dendrochronology the disturbance history was traced to at least the 1930s and, most likely, a strong wind episode from 1933 was the reason for the forest calamity that resulted in the nearly total destruction of the original stand. However, the affected forest was a planted Norway spruce monoculture, introduced and managed until at least the beginning of the 20th century, and not a natural forest. The windthrow niche was then used by beech, whose individuals preferentially chose mounds to grow, conserving the hummocky microtopography. Changes in soil evolutionary pathways brought about by wind-driven disturbance include both haploidisation (rejuvenation) and horizonation (differentiation). Evidence of soil rejuvenation includes a decrease in organic carbon content and an increase in pH in the upper parts of soils developed on mounds relative to the pH of undisturbed references soils. Soil texture was relatively homogenised in pits and mounds. Dating of the pit-and-mound microrelief by means of soil properties (organic carbon content, iron forms) was only partly successful. Although the young age of pits and mounds is evident, the actual age inferred from soil properties was underestimated by a few tens of years. Evaluation of factors potentially controlling the propensity to widespread treethrow suggests that the type of forest is a far more important variable than local abiotic factors of bedrock geology, regolith characteristics, and slope inclination.

Key words:
forest biogeomorphology,
pit-mound topography,
tree uprooting,
soils,
dendrochronology,
Sudetes

Introduction

Microrelief of forested hillslopes is shaped by ongoing interactions between abiotic processes of weathering and soil formation, downslope regolith displacement, surface runoff, and biotic factors, among which, tree growth and decay are of major importance (Roering et al. 2010; Šamonil et al. 2014; Amundson et al. 2015; Schaetzl and Thompson 2015). The generally slow rate of these processes may be upset and hastened by catastrophic events which disturb or even completely reorganise the geo-ecosystem. These disturbances may be natural and related to episodes of strong wind or heavy snowfall, or anthropogenic. In either case, the structure of forest stands is considerably altered and trees may break down or fall to the ground (Everham and

Brokaw 1996; Brázdil 1998; Mitchell 2012). If this happens, a range of consequences occurs in the abiotic environment, affecting forest floor topography, hydrological pathways and soil and regolith characteristics. These changes, in turn, control patterns of forest regeneration after disturbance and its further long-term evolution. The origin of pit-and-mound microtopography is probably the most striking example of biophysical interactions between trees, soils, and ground surface (Denny and Goodlett 1956; Phillips et al. 2008, 2017; Gabet and Mudd 2010; Šamonil et al. 2010a, 2013; Bobrovsky and Loyko 2016) and it does constitute a sort of ecological and soil memory. Its formation and present-day morphology may record events that occurred in the past and whose effects remain visible or available to detect by dedicated research methods from the field of dendrochronology (e.g. Lorimer and Frelich 1989), soil science (e.g. Šamonil et al. 2010b) or shallow subsurface geophysics (Pawlik and Kasprzak 2015). Thus, to explain the role of various factors in shaping forested hillslopes and their mutual interactions both the present and the past have to be taken into account, realising that, with time, the effects of past events become less and less evident.

The Rogowa Kopa locality in the Stołowe (Eng. Table) Mountains in SW Poland was selected to study the historical dimension of the pit-and-mound topography, which is exceptionally well developed and preserved at the study site (Pawlik et al. 2013). The study aimed to test the usefulness of an interdisciplinary approach to the problem of forest ecosystem disturbance by strong wind, i.e. what can be learnt about the reasons behind a massive windfall that occurred in the past, and its consequences. To do so, a few complementary lines of research have been followed. First, detailed examination of soil patterns within the pit-and-mound topography was carried out in order to evaluate both pathways of disturbance-driven soil evolution and the suitability of soils for indirectly dating the disturbance event. Second, dendrochronological studies were attempted with the aim of reconstructing forest stand composition and reaction to disturbance. Third, historical sources, including maps, were analysed in order to constrain the age of the major wind-driven disturbance whose date of occurrence is not known. Considering all these various sources of information together we are able to get a much better understanding of the biogeomorphic conditions, responses and feedbacks at sites affected by strong wind, as well as to distinguish between natural and anthropogenic factors at a disturbed forest site.

Study area

Physical environment

The pit-and-mound locality considered in this paper is located on the south-western slope of Mt Rogowa Kopa (790 m a.s.l.) in the Stołowe Mountains (referred to hereafter as RK), SW Poland (Fig. 1). The Stołowe Mountains have a tableland morphology, with thick sandstone layers of Upper Cretaceous age acting as caprock and cliff formers, whereas fine-grained sedimentary rocks, mainly mudstones and marls, are truncated by the mid- and lower slopes of escarpments and underlie extensive tracts of level relief (Migoń and Kasprzak 2015). However, Mt RK is an example of terrain elevation underlain entirely by fine-grained sediments (Rotnicka 1997), which build both the nearly planar top surface and the very steep slopes to the north, west, and south-west.

Steep hillslopes of Mt RK have been selected for detailed study because of their very well developed pit-and-mound microrelief, otherwise rare or indistinct in managed forests of the Sudetes Mountains due to their long history of management practices. Within the 2.3-ha south-facing slope site, 82 pairs of well visible treethrow mounds and pits were mapped. Their average surfaces are 7 and 6.5 m^2 and volumes 1.7 and 1.6 m^3 for mounds and pits, respectively. Altogether, they cover ca 5% of the research site (Pawlik et al. 2013, 2016). Local soils are classified mainly as Haplic Cambisols, 50–100 cm deep, with a texture of silt loam changing into loam in deeper soil horizons (Kabała et al. 2002). Mean annual rainfall at Pasterka (703 m a.s.l.) is 862 mm and mean annual temperature at Karłów (750 m a.s.l.) is 4.3°C (www.imgw.pl). The dominant wind direction is south-westerly and from this direction the highest mean wind speed, reaching 4 $m \cdot s^{-1}$, was recorded. Snow cover may be present from mid-No-

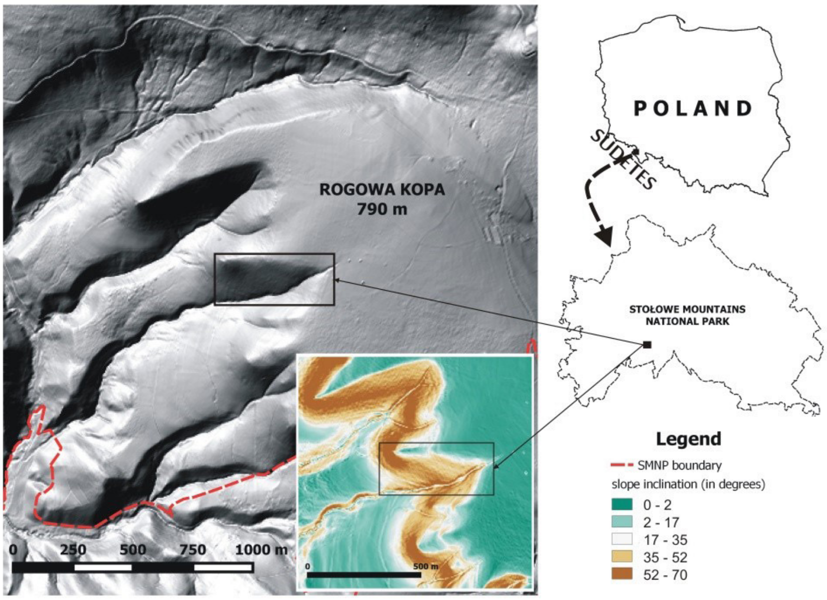


Fig. 1. Location of the study area in the Stołowe Mountains National Park; hillshade relief model of Mt Rogowa Kopa based on LiDAR data, site of detailed study indicated by black rectangle

vember to early April, although the actual number of days with snow is 54–161 days (Dubicki and Głowicki 2008).

Forest ecosystems

The Stołowe Mountains, similar to other parts of the Sudetes Mountains, were first partly deforested under the pressure of early settlements and the development of agriculture, manufacture and mining in the Middle Ages. Then, their species composition and structural characteristics were altered due to intensive forest management and industrial growth in the 18th and 19th centuries. In most part, this forest can be classified as a managed forest with simplified horizontal and vertical structure; with artificially introduced monocultures of Norway spruce (Świerkosz and Boratyński 2002), frequently of unknown origin and not native to the area of planting. Finally, since 1970s their health condition has decreased with industrial air pollution suspected as the main reason (Mazurski 1986). At present, forest cover reaches 90% of the Stołowe Mountains National Park (SMNP) (Miścicki 2008), but their natural stability is low, due to their health condition. In 1994 ca 8% of trees were classified as strongly damaged due to various abiotic, biotic and anthropogenic factors (Borecki and Wójcik 1996). According to data provided by foresters, the SMNP forests had been damaged by wind impact several times in the past, but most severely in 1834, 1913 and 1930 (Miścicki 2008). The last serious episode of hurricane wind took place in 1955 (Wojda and Zaborski 1959).

The studied slope of Mt RK can be divided into two distinct parts as far as vegetation pattern is concerned. The uppermost, gentle section of the slope is covered mainly by *Picea abies* (L.) H. Karst., although such tree species as *Fagus sylvatica* L., *Acer pseudoplatanus* L. and *Abies alba Mill.* are also present in smaller numbers. The distinguished forest division forms a narrow belt of ca 30 m, which constitutes a sort of a border between the nearly level surface terrain of the summit plateau and the slope which grows increasingly steeper as it extends down to the valley. The steep part of the slope, which is the exact object of the study, is covered by a significantly different plant association. There *F. sylvatica* sharply takes on the role of dominating species.

Materials and methods

Soil analysis

Soil sampling strategy

Soil profiles were located within three pit-and-mound pairs varying in their morphological expression. In each case a trench through the entire form was excavated, parallel to the slope inclination. Within each trench two profiles were cleaned and analyzed: (1) in the mound (M-profiles) and (2) in the pit (P-profiles). In adjacent places, apparently undisturbed by any tree uprooting process, three respective reference (control) soil profiles were made (U-profiles) at the same altitude. Soils were described according to the Guidelines for Soil Description (Jahn et al. 2006). Bulk samples of soil material were collected from each genetic horizon. Coarse fragments' volumetric content was estimated directly in the soil profiles.

Our initial hypothesis assumed that the degree of pit-and-mound degradation (lowering of mounds and infilling of pits) is positively correlated with O and A horizon thickness and organic carbon (OC) content within the upper soil horizons. In order to test the hypothesis, ten pit-and-mound pairs at different stages of degradation were chosen randomly within the study area. Within each pair, a horizontal section (Fig. 2) from the exterior part of the mound, through its top to the interior part to the pit was made. Four 50-cm-deep profiles were exposed in each section. In each profile, thickness, quality of organic horizons and the presence of A horizon were described. From the first 5 cm of the mineral part of the soil (0–5 cm depth) samples for OC content determination were collected. These profiles are labelled as I to IV.

Laboratory methods

Prior to laboratory analysis, living roots were removed, and samples were air-dried and sieved through a 2-mm-mesh steel sieve. Soil colour was described for samples in the moist and dry state using Munsell colour charts. The particle-size distribution was determined according to the Polish Soil Society (Systematyka Gleb Polski 2011) using the hydrometer method (Gee and Bauder 1986) without the removal of organic matter and secondary oxides. The organic carbon content (OC) was determined using rapid dichromate oxidation techniques (modified Tyurin method – digestion reagent: 0.068 M solution of $K_2Cr_2O_7$ in concentrated H_2SO_4; titrant: 0.2M solution of $FeSO_4$). Soil pH was measured potentiometrically in distilled water at 1:1 ratio and in 0.01M $CaCl_2$ at a 1:2 ratio (Thomas 1996; van Reeuwijk 2002). The amount of iron crystalline forms (Fe_d) was determined by extraction with dithionite–citrate–bicarbonate (DCB) solution (Mehra and Jackson 1960), while the content of amorphous forms of iron (Fe_o) was determined by extraction with ammonium oxalate (Schwertmann 1964). The final concentrations of Fe_d and Fe_o were measured by ICP-MS (Inductively Coupled Plasma – Mass Spectrometry).

Statistical analysis

Our soil data were statistically analyzed and graphically displayed using an R software environment for statistical computing and graphics (www.r-project.org). The following R packages were applied: stats,

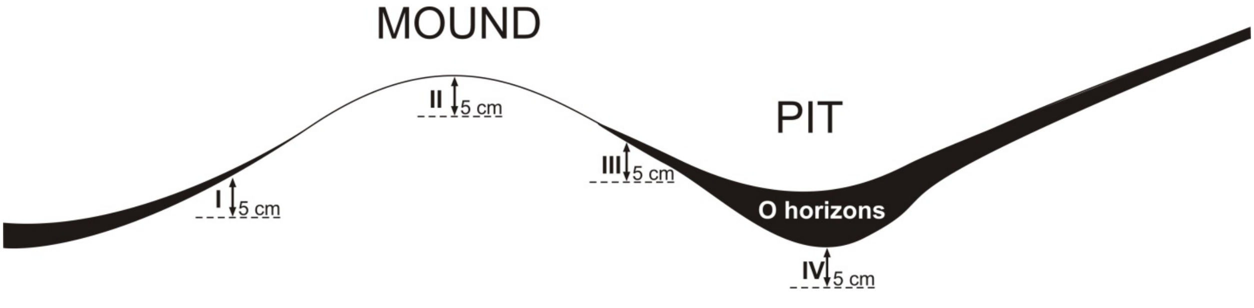


Fig. 2. Pattern of soil sampling in order to determine organic matter and carbon content within O and A horizons

aqp (Beaudette et al. 2013), corrplot (Wei and Simko 2016) and ggplot2 (Wickham and Chang 2016). We first checked for descriptive statistics and normal distribution of our data (the Shapiro–Wilk test of normality). Correlation coefficient by Spearman has been tested because half of our variables did not hold a normal distribution. Differences between major types of sites have been tested with the non-parametric Kruskal–Wallis rank sum test. We tested the null hypothesis, which says that for each variable there were no significant differences between our sites. For statistically different groups (mound, pit, control) for each variable we used a post-hoc two-sided Dunn test with correction for multiple comparisons according to the Bonferroni method (Dinno 2016; Ogle 2016). For all tests the level of significance has been accepted to p-value=0.05.

Dendrochronology

Field sampling and laboratory procedure

A total of 48 beeches (*Fagus sylvatica* L.), 2 sycamore maple (*Acer pseudoplatanus* L.) and 7 spruce (*Picea abies* L. H. Karst) trees were sampled by means of the Pressler increment borer with a diameter of 5 mm for dating purposes. Eleven sampled trees were growing within pits and mounds, whereas the remaining samples were taken from trees growing in the vicinity of pit-and-mound pairs. Additionally, five old-looking beech trees growing on the nearly flat, western spur of Mt RK, not affected by recent processes of mass transfer, were sampled to provide reference data. All samples were taken at standard breast height (1.3 m above the ground). The collected cores were dried and glued to special wooden slats. In order to make the ring structure clearly recognisable, the samples were carefully polished using increasingly finer sandpaper (240–360–500). The polished cores were scanned with a resolution of 3,200 dpi. Tree rings were measured and dated to 0.01 accuracy by means of the PAST4 (SCIEM 2007) and WinDendro Density (Regent 2010) software. The measurement accuracy was checked by means of COFECHA quality control analysis (Holmes 1983). In order to establish the real age of each sampled tree, 8 to 23 years were added to the calculated age at the breast height in case of beech and sycamore maple trees. 11 years were added to the breast height age (‘BH age’ from now on) of spruce trees. The period of time needed for these species to reach breast height was empirically evaluated by Paulson and Platt (1996) and Šebková et al. (2012).

Wood remains found in five mounds were taken for further anatomical analysis in order to recognise tree species which were uprooted. It was not possible, however, to make any cross-dating attempts, due to the absence of living trees of the same species which could be the basis for site chronology.

The growth patterns and origin of tree regeneration of old beech trees from Mt Rogowa Kopa

It was assumed that significant growth changes over the years could indicate the occurrence of some disturbance events within the stand. Evaluation of developed chronologies led to identification of years when the relative growth change was exceeded by 50 and 100 per cent. Percentage growth change rate was counted by means of the two methods. In the first (Nowacki and Abrams 1997) the growth change rate was counted as follows:

$$(M_2 - M_1)/M_1*100$$

where: M_1 is the average tree growth in the prior 10 years, M_2 stands for the average tree growth in the following 10 years.

In the second method, which was developed in order to determine the particular year in which the growth release patterns occurred, the growth change rate was counted in the following way:

$$(x_i - M_1)/M_1*100$$

where: M_1 is the average tree growth in the prior 10 years, x_i stands for tree growth in the particular year.

In order to distinguish more precisely the period when pit-and-mound microtopography was formed, past ecological conditions were evaluated by means of the tree-ring record. Based on estimation of the early-growth rate, it was possible to identify the type of radial growth patterns developed during the sapling stage and hence differentiate the gap, open stand or understory origin of trees (Lorimer and Frelich 1989; Paulson and Platt 1996). A null hypothesis that the analysed trees have the same early growth rate was assumed. The variables taken into account in the analysis were the age of trees at breast height and the total width of the innermost five and ten growth rings. In order to test the heterogeneity of the early growth rate, Ward's and k-mean methods of cluster analysis were applied. To test the hypothesis that no differences in the growth patterns of beech species occur, one-way ANOVA was conducted. In order to assess the statistical significance of differences in the early-growth rate between the selected groups, post-hoc analysis was carried out. All calculations (ANOVA, Ward's and k-mean) assumed a level of significance of p=0.05. Calculations were performed on standardised data.

Archive data sources – historical maps

In order to reconstruct changes in forest type, available historical topographic and forest maps were used. The oldest map, a German topographic map from 1919 (topographic data from 1881) at 1:25,000 scale, shows ground situation from the end of the 19th century. Further cartographic materials come from the 1920s, 1930s, 1960s and more recent periods (see the reference list of cartographic sources). Although this set of maps enabled us to study changes in the forest cover in rather coarse time intervals of decades, it was an important source of information for the time span not covered by the tree ring record. In the specific case of Mt RK, we were able to analyse changes in the forest stand for the last 150 years.

Results

Forest soil properties within pit-and-mound microsites

Soil texture

Soil texture of undisturbed soil profiles was silty loam turning in the deeper parts into sandy loam or clay loam depending on the substrate, specifically whether local mudstone layers are more sandy or more clayey. There were no statistically significant differences between soil profiles in terms of sand, silt and clay content (Kruskal–Wallis test, p-value=0.705, 0.219 and 0.308, respectively). All profiles showed a higher content of silt fraction; especially those places near the crest (RK01) (Table 1, Fig. 3). Horizons with a higher amount of silt are also sandwiched between the CA and C horizon in the middle-slope mound profile (RK02M). A similar situation was observed in the RK03 mound (the site in the lowest segment of the study plot).

Organic carbon content and its distribution

The distribution of organic carbon content in soil profiles was site-specific. In undisturbed soil profiles OC distribution reached the highest values (28–38 $g \cdot kg^{-1}$) in A horizons and gradually decreased with depth (Table 1, Fig. 4). In the mounds, OC content and its vertical distribution in the profile seemed to be consistent with the degree of mound degradation. In the most distinct form of a mound, RK02M, with the preserved fragment of a tree trunk (see Section 5.2), the highest OC values were noted in the middle part of the profile, while the near-surface part had values similar to those determined in the middle part of the undisturbed profile (RK02U) (Fig. 4). A similar OC distribution was found in the RK03M profile. The most leveled mound (RK01M) showed OC distribution similar to the undisturbed profile RK01U. Generally, pit forms contained significantly more OC than mounds (Kruskal–Wallis test, p-value=0.0025; Dunn test, padj.=0.002). The highest OC concentrations were determined in RK01P.

Organic matter quality and OC content in the 0–5 cm mineral layer (Table 2) shows some differentiation within pit-and-mound forms and in relation to the degree of their degradation. In most of these forms, organic horizon (only Oi horizon) occurs discontinuously or is absent on the top of the mound. Continuous Oi horizon cover was present only in the least pronounced forms. Complete differentiation of organic horizons into sub-horizons was found only in pits. The presence and thickness of A horizons is related to location within the horizontal section of a pit-and-mound pair and to the

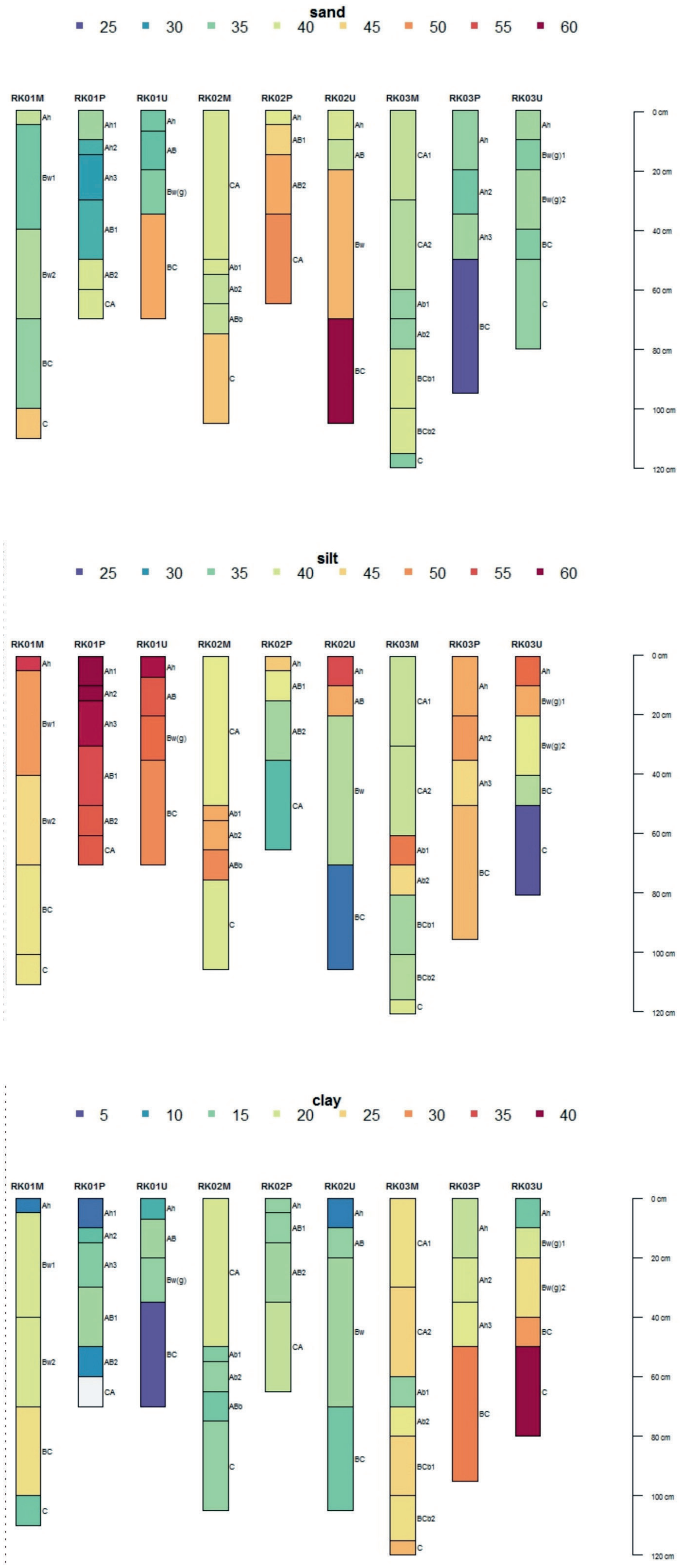


Fig. 3. Sand, silt and clay content (%) in soil profiles under investigation (M: mounds, P: pits, U: undisturbed, control profile)

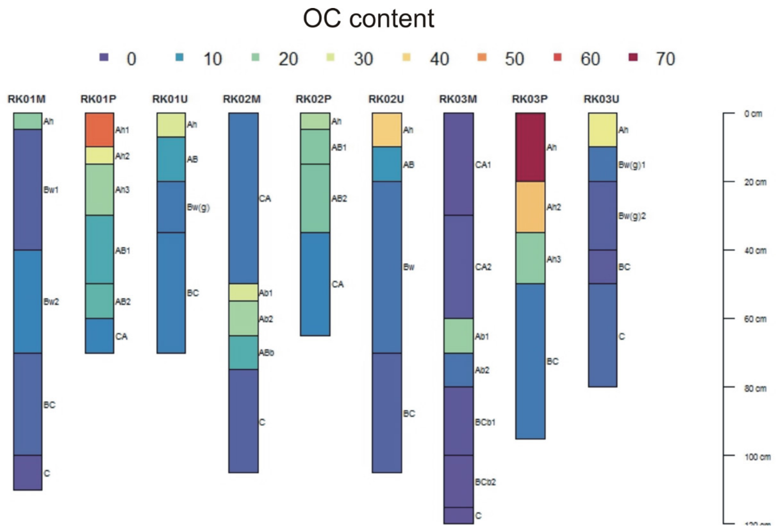


Fig 4. Organic carbon content in the analyzed soil profiles

distinctiveness of the form. A horizons occur in all pits, whilst in profiles I, II and III it was found only in less pronounced mounds reaching 1–5 cm. Variability in OC content within the 0–5 cm horizon of mineral material mirrors the occurrence of A horizon. The highest OC concentration in 90 per cent of cases was noted in the pits (profile IV: 22–81 $g \cdot kg^{-1}$) and the lowest on top of the mounds (profile II: 2–20 $g \cdot kg^{-1}$). Forms with weaker morphological expression show smaller differences in OC content throughout the pit-and-mound relief. When compared to other microsites, OC concentrations in shallower pits were lower, but higher on the top of mounds (Table 2).

Soil chemical properties

Chemical properties of soil profiles varied significantly by location within pit-and-mound forms and control sites, as well as with depth of soil profiles (Table 2, Fig. 5). In all control profiles and pits, soil pH values gradually increased with depth (significant correlation at $p<0.05$) (Fig. 6), while in mounds, pH vertical distribution was more differentiated (no correlation). In the most degraded form (RK01), pH was similar between mound, pit and undisturbed site. The highest variability of soil pH values was determined in RK03M. Here, in the top 30 cm of soil material, the pH was higher than in the middle part of the profile (probably buried Ab horizon as indicated by higher OC content) (Figs 4 and 7).

Concentrations of dithionite (Fe_d) and oxalate (Fe_o) forms of iron in the analyzed soils were very different and related to two variables: location and depth (Fig. 7). Fe_d content in RK01U and RK02U showed the maximum values in Ah horizons around 12–16 $g \cdot kg^{-1}$, then decreased gradually to reach 6–8 $g \cdot kg^{-1}$ in Cr horizons. Fe_o content indicated similar distribution in these two profiles, with the highest content in the uppermost horizons and the lowest in their deepest parts. RK03U showed a different distribution of Fe_d and Fe_o concentrations. Here, Fe_d concentration was around 50 per cent higher than in the other undisturbed profiles. Moreover, the maximum Fe_d content (19 $g \cdot kg^{-1}$) was determined in BC horizon. Fe_o content in RK03U increased with depth. All profiles located in the mounds showed similar Fe_d distribution, i.e. a gradual increase to a depth of around 50–80 cm in RK01M and RK02M, and to 80–115 cm in RK03M, and then a slight decrease in C horizons. In RK02P and RK03P an increase of Fe_d and Fe_o content with soil depth was determined. Content of iron forms in RK01P, an example of an infilled pit, showed irregular distribution when compared to other pits.

Table 1. Soil physical and chemical properties

Depth [cm]	Horizon	OC [g kg^{-1}]	pH [H_2O]	Fe_d [g kg^{-1}]	Fe_o [g kg^{-1}]	Fe_d/Fe_o
Profile RK01U: undisturbed soil profile						
0–7	Ah	28.4	4.2	16.1	3.5	0.22
7–20	AB	11.4	4.4	15.0	3.2	0.21
20–35	Bw(g)	6.8	4.6	6.0	2.9	0.49
35–70	BC	7.6	6.8	6.4	2.8	0.43
Profile RK01M: mound						
0–5	Ah	19.1	4.4	12.1	4.0	0.33
5–40	Bw1	3.8	4.5	15.5	2.7	0.17
40–70	Bw2	8.1	5.3	18.9	3.1	0.14
70–100	BC	4.7	6.7	21.6	3.6	0.14
>100	C	2.5	7.1	16.2	2.7	0.22
Profile RK01P: pit						
0–10	Ah1	50.5	4.0	5.7	4.2	0.73
10–15	Ah2	30.4	4.0	6.2	3.9	0.63
15–30	Ah3	20.9	4.3	6.9	3.7	0.54
30–50	AB1	12.7	4.9	6.2	3.3	0.54
50–60	AB2	14.4	6.5	3.7	2.1	0.57
>60	CA	8.1	6.4	9.9	3.3	0.33
Profile RK02U: undisturbed soil profile						
0–10	Ah	37.8	3.9	11.5	3.3	0.29
10–20	AB	10.4	4.2	13.9	3.5	0.25
20–70	Bw	6.2	4.5	9.9	3.1	0.31
70–105	BC	4.1	5.8	8.6	2.0	0.23
>105	Cr					
Profile RK02M: mound						
0–50	CA	6.7	4.4	11.6	2.5	0.21
50–55	Ab1	28.3	4.1	12.5	2.7	0.21
55–65	Ab2	21.8	4.2	13.9	2.8	0.20
65–75	ABb	13.3	4.1	14.3	2.7	0.19
75–105	C	3.8	4.4	12.3	2.1	0.17
Profile RK02P: pit						
0–5	Ah	23.2	4.3	15.3	2.4	0.16
5–15	AB1	17.8	4.2	15.0	2.7	0.18
15–35	AB2	17.0	4.6	16.9	2.7	0.16
35–65	CA	8.1	4.7	21.0	2.8	0.13
Profile RK03U: undisturbed soil profile						
0–10	Ah	31.6	5.0	15.7	2.9	0.18
10–20	Bw(g)1	6.2	4.8	15.4	2.8	0.18
20–40	Bw(g)2	3.6	5.0	14.0	2.7	0.19
40–50	BC	2.9	5.3	18.6	3.2	0.17
50–80	C	5.1	6.2	n.d.	n.d.	n.d.

Table 1. Continued

Profile RK03M: mound						
0–30	CA1	2.2	5.8	12.8	2.8	0.22
30–60	CA2	3.0	4.9	15.6	2.6	0.17
60–70	Ab1	20.4	4.4	16.0	3.8	0.24
70–80	Ab2	6.0	4.6	12.9	3.4	0.27
80–100	BCb1	2.6	4.8	15.0	3.2	0.21
100–115	BCb2	2.3	5.1	19.8	7.3	0.37
>115	C	2.0	5.2	12.0	3.7	0.31
Profile RK03P: pit						
0–20	Ah	63.9	6.2	16.6	2.2	0.13
20–35	Ah2	39.9	6.9	15.9	2.7	0.17
35–50	Ah3	19.1	7.1	17.5	2.6	0.15
50–95	BC	6.8	7.3	20.7	2.5	0.12

n.d. – not determined

Table 2. Selected soil properties within 10 randomly chosen pit-and-mound pairs (*OC content in the 0–5 cm depth layer of mineral horizon)

Section No	Location		I	II	III	IV
1 Indistinct form (denuded)	horizon thickness [cm]	Oi	3	2	5	9
		Oe	absent	absent	absent	15
		Oea				4
		Oa				5
		A		1-2	1-2	17
	OC content [g·kg^{-1}]*		7.0	9.0	33.4	24.1
	Munsell colour		2.5YR 5/4	2.5YR 6/4	2.5YR 3/2	2.5YR 3/2
2 Indistinct form	horizon thickness [cm]	Oi	4	4	7	12
		Oea	absent	absent	absent	6
		Oa				1
		A	1-2	3	5	20
	OC content [g·kg^{-1}]*		8.6	14.8	14.7	20.3
	Munsell colour		2. 5YR 5/4	2.5YR 5/4	2.5YR 4/2	2.5YR 4/2
3 Indistinct form with gravel on the top	horizon thickness [cm]	Oi	4 (discontinuous)	2 (discontinuous)	6	10
		Oe	absent	absent	3-5	4
		Oea			3-5	12
		A			absent	14
	OC content [g·kg^{-1}]*		15.3	6.0	28.2	65.5
	Munsell colour		10YR 6/4	10YR 6/4	2.5YR 5/4	2.5YR 3/2
4 Distinct form without preserved root system	horizon thickness [cm]	Oi	absent	2	4	7
		Oe		absent	absent	20
		Oa				7
		A				16
	OC content [g·kg^{-1}]*		16.7	4.4	9.7	52.9
	Munsell colour		2.5YR 4/4	2.5YR 6/4	2.5YR 4/3	2.5YR 3/2
5 Distinct form without preserved root system	horizon thickness [cm]	Oi	4	2 (discontinous)	4	9
		Oe	absent	absent	absent	10
		Oea				6
		A				10
	OC content [g·kg^{-1}]*		11.3	3.0	14.1	34.1
	Munsell colour		2.5YR 4/3	2.5YR 6/4	2.5YR 4/3	2.5YR 3/2

Table 2. Continued

6 Distinct form without preserved root system	horizon thickness [cm]	Oi	4 (discontinuous)	2 (discontinuous)	9	12
		Oe	absent	absent	absent	9
		Oea			3	absent
		Oa			absent	2
		A			1-2	18
	OC content [g·kg^{-1}]*		6.6	2.2	13.3	70.8
	Munsell colour		2.5YR 6/4	10YR 7/6	2.5YR 5/4	10YR 3/3
7 Distinct form with preserved root system	horizon thickness [cm]	Oi	4	2	7	10
		Oea	absent	absent	absent	7
		A				20
	OC content [g·kg^{-1}]*		9.3	3.8	15.4	43.8
	Munsell colour		2.5YR 4/4	2.5YR 5/4	2.5YR 4/4	2.5YR 3/2
8 Distinct form with preserved root system	horizon thickness [cm]	Oi	3 (discontinuous)	2 (discontinuous)	3	10
		Oea	absent	absent	absent	8
		A				25
	OC content [g·kg^{-1}]*		4.2	11.3	10.1	32.8
	Munsell colour		2.5YR 6/4	2.5YR 5/4	2.5YR 5/4	2.5YR 4/3
9 Distinct form with preserved root system	horizon thickness [cm]	Oi	3 (discontinuous)	2 (discontinuous)	6	11
		Oe	absent	absent	absent	4
		Oa				6
		A	absent	absent	absent	10
	OC content [g·kg^{-1}]*		3.7	4.1	9.3	52.1
	Munsell colour		2.5YR 6/4	2.5YR 5/4	2.5YR 4/4	2.5YR 3/3
10 Distinct form with preserved spruce trunk	horizon thickness [cm]	Oi	4	absent	6	11
		Oae	absent	absent	absent	5
		A				20
	OC content [g·kg^{-1}]*		11.9	3.1	9.1	81.1
	Munsell colour		2.5YR 5/4	2.5YR 6/4	2.5YR 6/4	2.5YR 4/3

Dendrochronological record

Site homogeneity and the approximate age structure of the forest

The results derived from the COFECHA program (Holmes 1983) showed very weak inter-correlation between ring-series of all trees sampled within the study site (0.18, p<0.05) (Fig. 8). Following Grissino-Mayer (2001), a low level of correlation may suggest that the growth patterns of sampled trees were highly differentiated within their lifetimes. Within the study site, the evidence of low site homogeneity due to high variability of growth disturbance, both in space and time, was found by Pawlik et al. (2013). However, four out of five old beech trees growing on the western spur of Mt Rogowa Kopa, considered as the reference site, showed a high inter-correlation, reaching the level of 0.49 (p<0.05). Results of tree-ring analysis demonstrate that beech trees within the study site are of similar, rather young age. The average BH age of 55 trees is 51.4 years and as much as 65 per cent of trees are between 45 and 55 years old. Beech and spruce show a similar BH age range. Two sycamore maple trees are older (89 and 75 years, BH age) (Fig. 9). Accounting for the period of time needed to reach breast height (Paulson and Platt 1996; Šebková et al. 2012), the tree-ring data indicate that most trees began to grow in the period between the 1930s and 1950s (Fig. 10).

Tree ages as temporal constraints of pit-and-mound microrelief

Dating of the minimum age of mounds was conducted by establishing the age of four beeches, two sycamore maples and two spruce individuals grow-

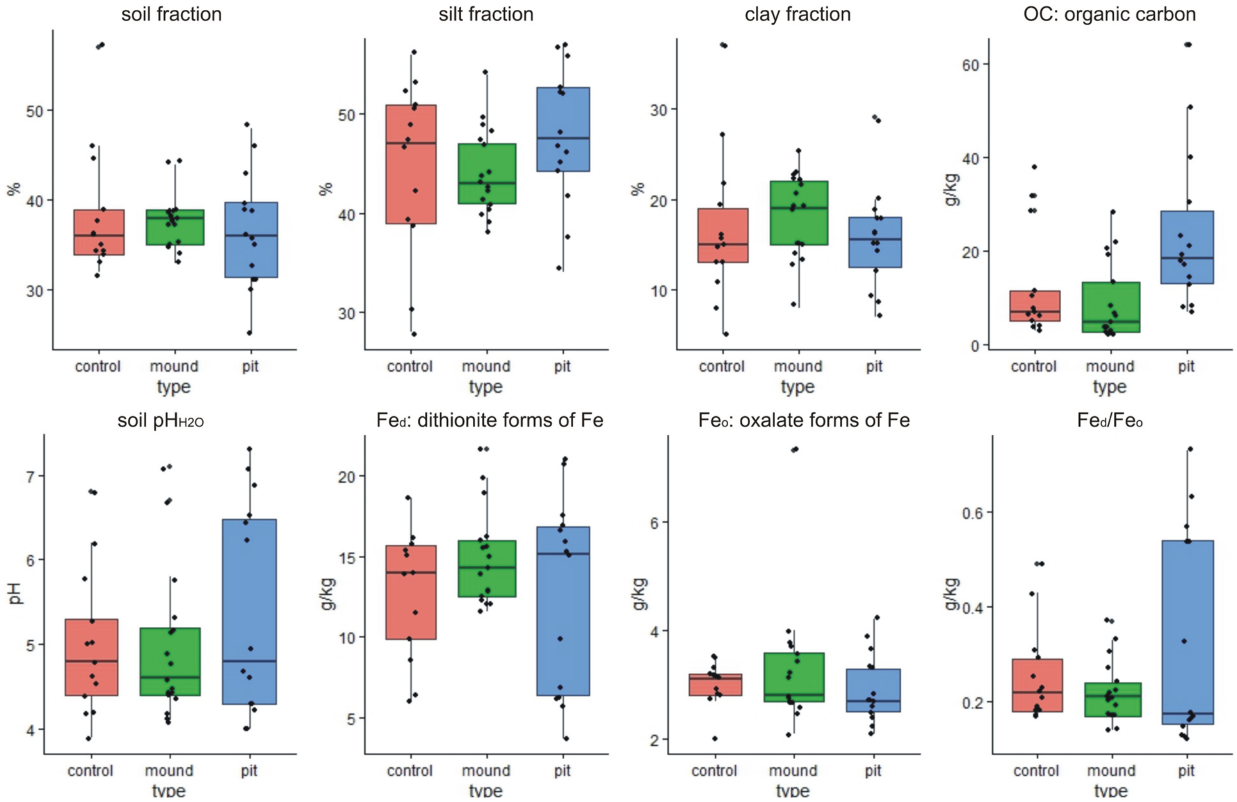


Fig. 5. Boxplots of variable distribution for each type of soil profile: mound, pit and control, with individual observations marked (black dots)

ing on mounds. The minimum age of pits was constrained by the ages of three beech trees living inside them.

The ages of trees occupying treethrow mounds are within the same BH age range as the remaining part of the local beech population, i.e. 48, 49, 51 and 54 years. Two spruce individuals are of almost identical age (47 and 59 years), whereas sycamore maple trees are older, 75 and 89 years. BH ages yielded by beech trees growing in pits were similar – 48, 49 and 51 years. Adding the empirically derived period of time needed to reach breast height (Paulson and Platt 1996; Šebková et al. 2012), the minimum age of dated mounds can be estimated at 56–60 years for beech and spruce and 98–112 years for those overgrown by sycamore maple individuals. The minimum age of three dated pits is between 56 and 74.

In five cases remains of buried wood were collected and all five turned out to be spruce individuals, strongly indicating the possibility that forest composition prior to the origin of pit-and-mound microtopography was different from the contemporary one, and spruce was the dominant species.

Patterns of growth

The currently dominant species on the study site is beech, which is shade-tolerant and thus able to germinate under closed canopies. Beech trees reach breast height in 8 to 23 years (Paulson and Platt 1996) and can survive as seedlings or small sapling forms in understory conditions. The growth release of this species is usually not abrupt and depends on site characteristics (Trotsiuk et al. 2012). The correlation coefficient between the age of trees at breast height and the total width of the innermost five and ten tree-rings is negative, at -0.41 and -0.43, respectively. However, the detailed analysis of the plot (Fig. 8) indicates various relations between the variables and suggests that radial growth patterns of trees from Mt RK are age-dependent. By means of Ward's and k-mean methods, three clusters were obtained. The first cluster includes relatively young individuals whose first 5–10 tree rings are the widest. The second cluster comprises trees which produced growth rings of moderate size over the period. The third contains relatively old trees which formed the narrowest rings on average (Fig. 8). The F-test for breast-height age and innermost tree-rings at breast

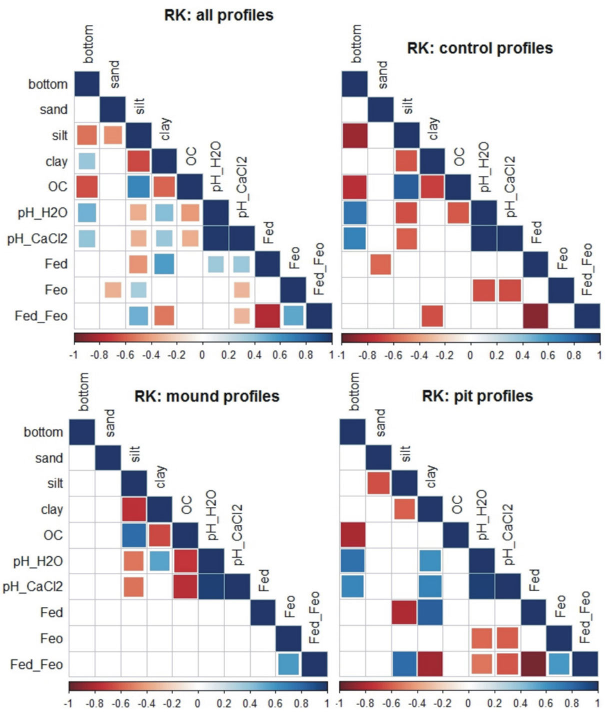


Fig. 6. Correlation coefficient matrices showing relationships between analyzed variables for all three types of microsite and matrix for all types combined. Spearman rank correlation coefficient was applied. Only significant relationships have been shown at $p<0.05$

height yielded results of 25.42 and 33.15, respectively. Therefore, the null hypothesis that the analysed trees have the same early growth rate was rejected. The post-hoc analysis of variance shows that statistically significant differences between the selected groups occur.

A different pattern of growth was recorded in beech trees at the reference site, on the western spur of Mt RK. First, they are much older than those from the pit-and-mound riddled slope. Their average age at breast height is 149 years, whilst the oldest tree is 175 years old. Tree-ring series, visualised as 10-year moving averages, show variable growth histories of each specimen over the years (Fig. 10). Although all trees grew according to the similar model until the second decade of the 20th century – with well-marked short-term fluctuations and poorly visible long-term trend, the situation changed rapidly afterwards. Trees REF01 and REF03 revealed a striking growth take-off and considerable short-term growth variability. Trees REF02, REF04 and REF05 started to form distinctly wider growth rings in the 1940s. Years with considerable growth release (>50% and >100%) are not repeatable by all individuals; nevertheless, they occur most frequently in the first half of the 20th century. Growth release can also be observed in the 1950s and 1960s – and earlier, in the second decade of the 20th century. At tree REF04, similar phenomena also occurred in the 1980s and 1990s. Growth release of some individuals on the western spur of Mt RK in the first half of the 20th century corresponds well to the beginning of growth of trees on the slope (Fig. 10).

Analysis of cartographic sources

The contemporary forest within the research site is classified as fertile Sudetic beech stand (*Dentario enneophyllidis-Fagetum typicum*). Although it is

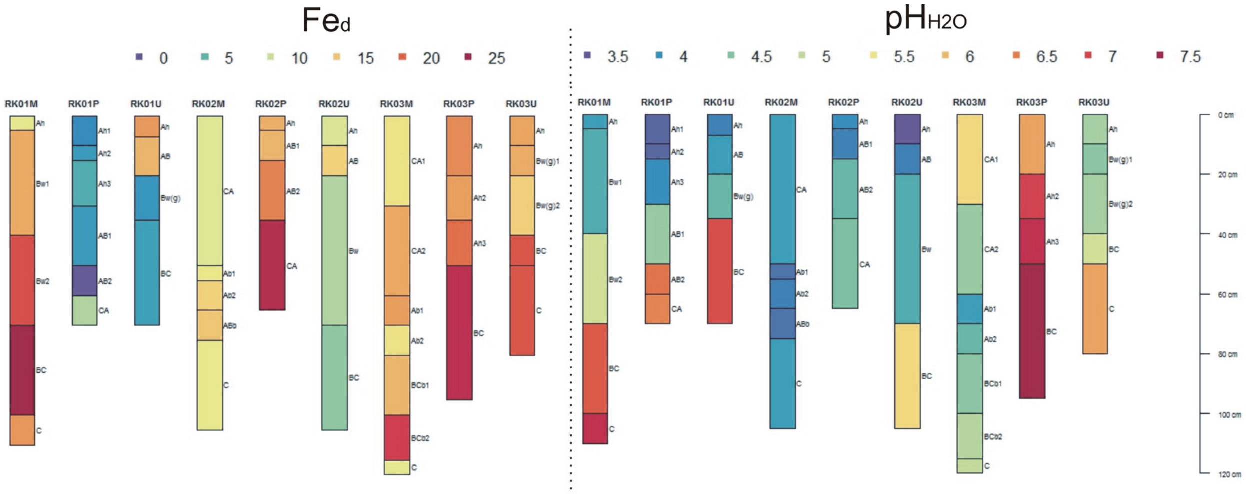


Fig. 7. Concentrations of dithionite (Fe_d) and soil pH related to profile depth and diagnostic horizon

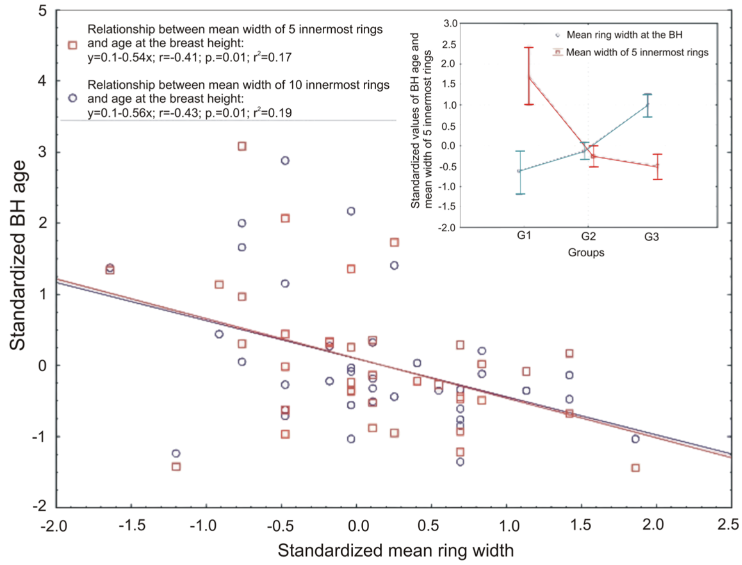


Fig. 8. Relationship between age and mean ring width of sampled trees (larger diagram) and comparison between breast height (BH) age and mean width of 5 innermost rings (smaller diagram) (original)

considered as a nearly natural one (TMNP 2009), maps from the early 20th century suggest that a major change in forest composition took place in the relatively recent past. On the German topographic map at 1:25,000 scale, originally made in 1881 and updated in 1919, the area of interest was marked as coniferous forest (Fig. 11). The same symbol is repeated on subsequent maps from 1922 (Czech, 1:75,000) and 1938 (German, 1:100,000), indicating spruce plantations. However, the map of the Duszniki Forest District dated to 1964 shows young beech forest (13 years old), with a much older (>80 years) beech community next to it. Sources from 1961, used without update to produce another topographic map in 1982 (scale 1:50,000), indicate the area of concern as largely deforested, with singular trees. On the topographic map at 1:25,000 scale from 1983 (with spatial data from 1977) the area was shown as reforested with mixed forest (with hornbeam and Norway spruce). These sources to-

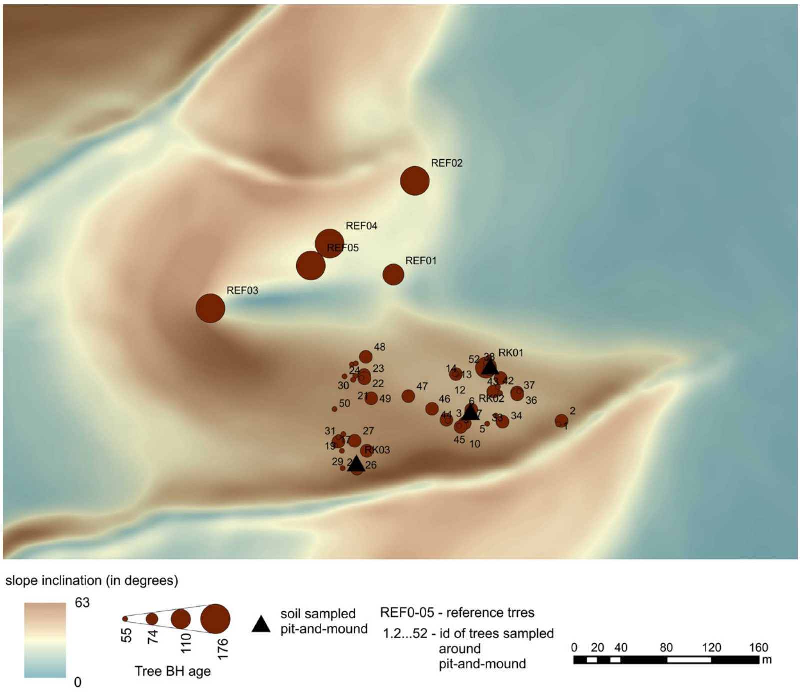


Fig. 9. Trees sampled for dendrochronological analyses with indicated BH (breast height) age in years

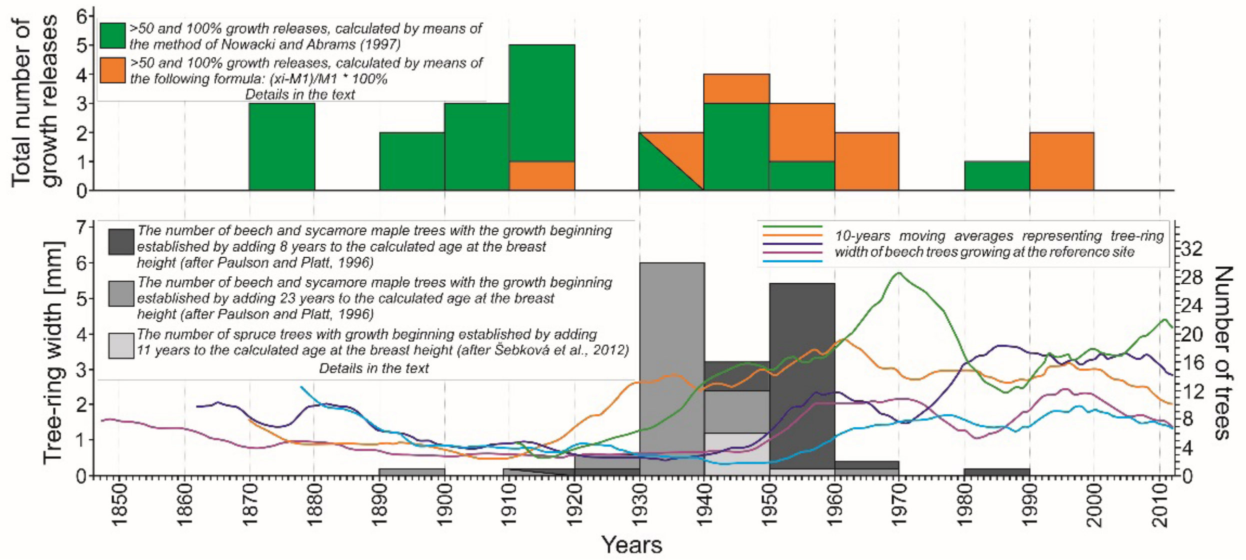


Fig. 10. Calculated growth releases against tree-ring width (original)

gether indicate that between the late 1930s and late 1950s spruce forest disappeared and was replaced by the contemporary mixed forest, with dominant beech.

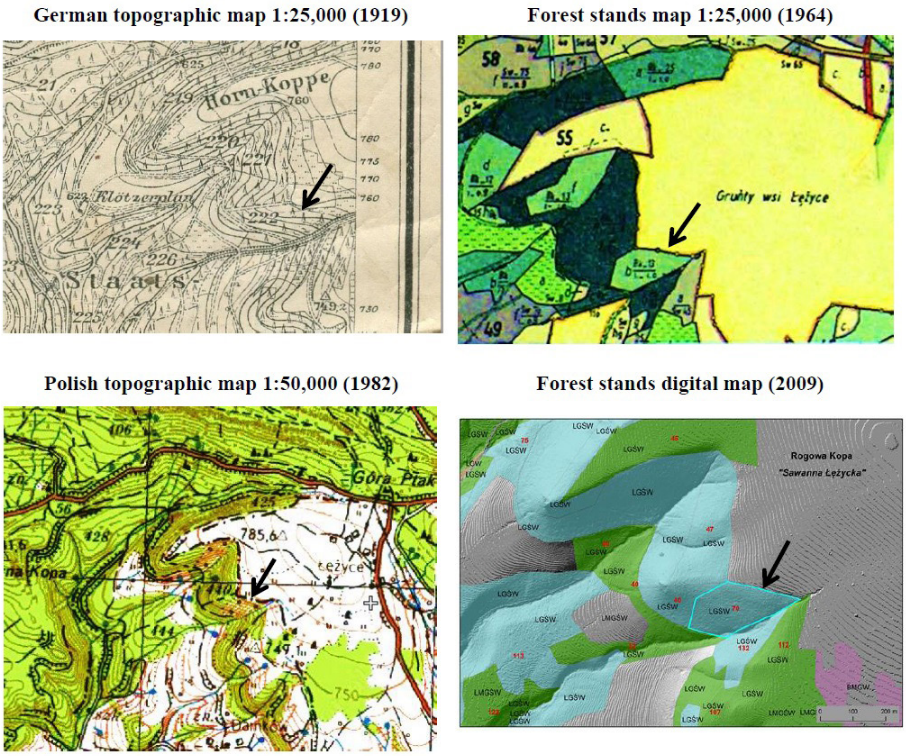
Discussion

History of forest disturbance

The various sources and lines of evidence suggest the following forest history and surface disturbance at the Mt RK site. In the late 19th and early 20th century spruce mono-stand existed, apparently replacing an earlier, natural forest community. Old (>150 years) beech individuals on the western spur of the plateau are probably surviving remnants of the ancient mixed forest. The spruce forest was depicted on an early topographic map and the findings of spruce wood remains within mounds are consistent with the cartographic picture. The introduction of spruce brought about various changes and environmental consequences, including the development of the rather shallow root systems typical of spruce and hence, disturbance and mixing of the near-surface regolith layer. The spruce forest was more prone to wind damage, which resulted in occasional uprooting of individual trees and the emergence of canopy gaps. These circumstances were opportunistically used by beech trees growing next to fallen spruces to accelerate their growth, the record of which can be read from tree ring patterns.

Further pieces of evidence to reconstruct the history are the early 1960s forest map, which indicates the presence of a young mixed forest, approximately 13 years old at that time, and the results of age determinations of trees growing on mounds. They are within the 60–75 years range, indicating that mounds must have originated prior to 1960. Thus, it is inferred that between the 1930s and late 1950s an episode of wind damage must have occurred which devastated spruce stands, causing widespread uprooting and the origin of pit-and-mound relief. Within this period, two significant catastrophic wind events occurred, in 1933 and 1955 (Pawlik 2012), and either could have resulted in widespread forest damage. However, in the light of information provided by the map, and given the lag time necessary to convert a root plate into a soil-mantled mound suitable for growth of a new generation of trees, the year 1933 appears more likely. Most of the fallen trees were probably removed by the forest service and only a few buried trunks remained within the site.

Thus, the most recent history of the site started with the origin of pit-and-mound relief in the 1930s. It has become successively colonised by beech, with minor admixture of sycamore maple and spruce. Bradshaw et al. (2010) showed that beech frequently forms monospecific stands and hypothesised that


German topographic map 1:25,000 (1919)

Forest stands map 1:25,000 (1964)

Polish topographic map 1:50,000 (1982)

Forest stands digital map (2009)

Fig. 11. Mt Rogowa Kopa forest history on topographic maps from different periods. See text for explanation

its early spreading over Europe probably needed a natural or anthropogenic disturbance factor. It was also suggested that formation of beech-dominated stands is favoured by abandonment of forest management (Jaworski and Pach 2014). It is likely that both factors have played a role at the study site.

Beech trees appear better adjusted to local environmental conditions and more recent windthrows recorded in the Sudetes, e.g. imposed by the Kyrill storm in 2007, did not affect the site. However, occasional uprooting does take place and 15 uprooted trees at different stages of decomposition, hence probably of different ages, were documented within the research site (Pawlik et al. 2013). Interactions between biotic factors and physical processes have led to the gradual evolution of the pit-and-mound topography towards more a subdued form and affected pedogenesis.

Trends in pedogenesis in the pit-and-mound environment

The origin of pits and mounds diversified the topography of the forest floor and set the stage for multidirectional pedogenesis. Generally, soils within pit-and-mound microsites undergo relative rejuvenation in comparison with undisturbed soil environments (Stephens 1956; Beke and McKeague 1984; Veneman et al. 1984; Schaetzl 1990; Šamonil et al. 2010a). This generalisation is consistent with the model of proisotropic pedoturbation, implying simplification of the soil profile within a regressive pathway of pedogenesis (Johnson et al. 1987). However, looking at soil profiles in detail, one can identify the effects of both haploidisation and horizonation (differentiation).

At Mt RK, evidence of soil haploidisation includes a decrease in organic carbon content and a pH increase in the upper parts of soils developed on mounds, in comparison with undisturbed soils. Soil texture was relatively homogenised in pits and mounds in comparison with reference soils (Fig. 3). At the same time, many soil properties differ in the analyzed profiles. Soil pH, organic carbon content and forms of iron concentration show irregular distribution, related to burial of old soils (pedorelicts; Pawluk and Dudas 1982; Schaetzl 1990; Šamonil et al. 2010a, 2015). Further changes in soil morphology include the appearance of discontinuous miner-

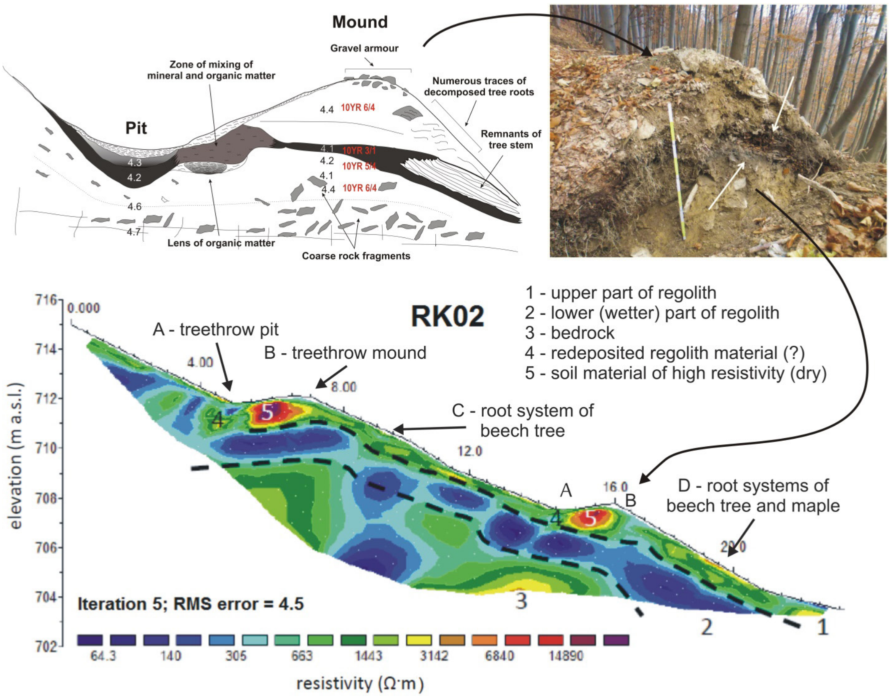


Fig. 12. A synthesis of field data about features of RK02 microsite (middle-slope position) based on ERT (Pawlik and Kasprzak 2015) and soil profile morphology

al horizons and buried organic horizons in mounds, increased solum thickness on mounds, and topsoil armouring due to bedrock mining. Similar changes have been reported from other regions (Pawluk and Dudas 1982; Beke and McKeague 1984; Veneman et al. 1984; Phillips et al. 2008, 2015; Šamonil et al. 2015). Partial inversion of soil horizons, reported by Schaetzl (1986) and Šamonil et al. (2015), was evident when soil pH (Fig. 7) and colour (Pawlik et al. 2013) in mounds was compared to control profiles.

Our previous results of ERT (Electrical Resistivity Tomography) survey confirmed that pits and mounds are moist and dry microsites, respectively (Fig. 12). The latter, being warmer, drier and with lower soil bulk density, are more favourable places for tree germination (Pawlik and Kasprzak 2015). Findings from the research site, where on 21 per cent of mounds a tree grew (Pawlik et al. 2013), are consistent with results from the Novohradské hory elsewhere in the Bohemian Massif, where it has been documented that some tree species preferably colonise mounds rather than pits. European beech and silver fir regenerate or resprout better on mounds than Norway spruce does (Šebkova et al. 2012). Such a positive relationship, with trees repeatedly occupying the same places affecting processes of weathering and pedogenesis, has been termed the “self-reinforcing pedologic influence of trees” (Phillips and Marion 2006) and described as the “non-random impact of trees” (Šamonil et al. 2010a, b).

The content of iron forms varied significantly among different locations within pit-and-mounds. Deeper pits (RK02P and RK03P) contain more Fed and have lower Fe_o/Fe_d values than soil profiles made through the adjacent mounds. Intensification of pedogenesis can be attributed to higher organic matter accumulation, higher moisture and lower pH (Schaetzl 1990). Pit-and-mound forms classified as recent on morphological grounds showed Fed content differentiation similar to the following sequence of soil-forming processes intensity: pit > undisturbed profile > mound, as described by Schaetzl (1990). RK01, with very leveled relief, showed an opposite relationship, with intensification of soil-forming processes in the mound. Šamonil et al. (2010b) showed that undisturbed reference profiles were richer in Fe_o and exhibited higher Fe_o/Fe_d values than treethrow mounds and pits. Such variability was observed in RK02 form while results for RK03M and RK03U were similar.

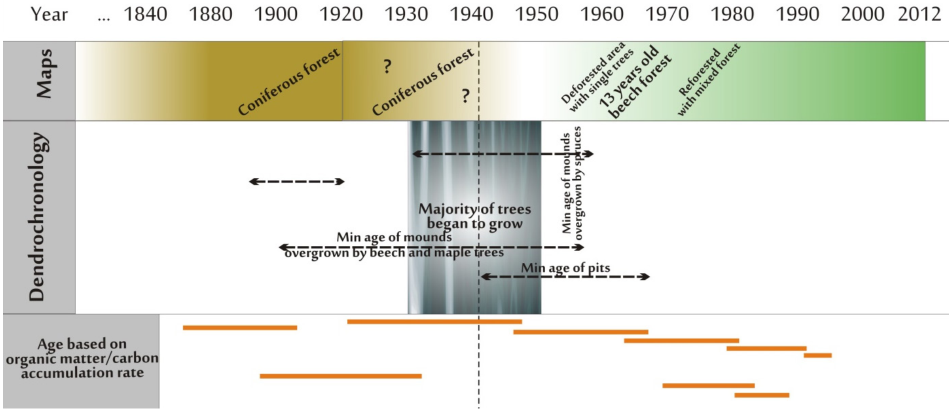


Fig. 13. Time frames of the forest stand history at Mt Rogowa Kopa. Synthesis based on map resources, dendrochronology and soil studies (original). Forest type indicated by question marks is considered as uncertain because the maps might have not been fully updated

The irregular distribution of Fe_d content in the profiles located in mounds can be attributed to the presence of old O and A horizons buried in the process of tree uprooting. Its distribution was positively correlated with differentiation of OC content in these profiles. On the other hand, the irregular distribution of iron forms in RK01P was most probably related to degradation processes and subsequent infilling of the pit, as suggested by the significantly higher Fe_o/Fe_d ratio values in this profile than in other pits.

Can soil properties within pit-and-mounds help to establish their ages?

Dendrochronological data and cartographic sources helped to establish the age of pit-and-mound topography on the Mt RK slope with relatively good accuracy (Fig 13). In this way, background was created to test methods of dating pit-and-mound associations using selected soil characteristics, namely (1) OC content and its distribution in the soil profiles and in horizontal sections through pit-and-mound pairs and (2) iron form concentration and its ratio values in soil profiles within pit-and-mound microsites and at undisturbed control sites. The conceptual basis was provided by Dümig et al. (2011) who determined OC accumulation rates on the basis of soil chronosequence in the Swiss Alps consisting of both the proglacial area and its surroundings (>700 years). The rates varied from 0.09 to 0.19 $g \cdot kg^{-1} \cdot a^{-1}$, with the lowest values obtained for 70-year-old soil and the value 0.14 $g \cdot kg^{-1} \cdot a^{-1}$ for the reference soil outside the proglacial area (>700 years). These values of OC accumulation rates for 70- and >700-year-old soils were used to estimate the temporal framework of pit-and-mound microtopography on Mt RK, although it needs to be considered that climatic conditions are not fully comparable.

Another parameter which reflects the relative age of soils and the degree of its disturbance is the content of free (Fe_d) and active (Fe_o) forms of iron and its ratio. An increase of Fe_d simultaneously with a decrease of Fe_o/Fe_d is considered evidence of progress in soil-forming processes (Šamonil et al. 2010b).

Ages estimated from OC accumulation rates determined by Dümig et al. (2011) indicate that the more degraded pit-and-mound pairs have a longer history. However, exceptions exist in both groups, e.g. an apparently young section no. 8 proved unexpectedly old. In general, however, there is a mismatch between estimated ages of pit-and-mound formation and the likely age of forest disturbance inferred from more reliable sources. The former are too young in respect to the probable age of the wind calamity on Mt RK.

Many authors (e.g. Dümig et al. 2011; Egli et al. 2012) emphasised the potential influence of local factors, particularly microrelief and microclimate, on OC accumulation rates. In the case analyzed here it is assumed that in the first stage, after uprooting and pit-and-mound formation, a high amount of organic matter was accumulated in the pits. Due to higher moisture, decomposition of organic matter in the pits was delayed in comparison with the adjacent sites. Afterwards, denudation of adjacent slopes and treethrow mounds in particular resulted in gradual infilling of the pits and the subsequent drop in OC content. Such a relative decline of OC was observed in less pronounced pit-and-mound forms. Because of the rather irregular pattern of OC accumulation in the pits, mounds seem more suited to establishing a temporal framework of pit-and-mound topography. OC accumulation in mounds, if not disturbed by any extreme phenomenon, should increase with time. Moreover, mounds hardly ever show an irregular pattern of OC accumulation rates, whereas within pits another factor of OC differentiation is moisture content.

Controls and lifetimes of pit-and-mound topography

Data from Mt RK allow us to add to the discussion about the role of factors controlling the origin and evolution of pit-and-mound topography and its persistence. Strong wind events are the primary causative factors, but windthrow effects are often localised. Potential local controls are related to regolith characteristics, topographic factors such as aspect in respect to dominant wind or slope inclination, and features of the forest community itself (Everham and Brokaw 1996; Mitchell 2012). In the specific case of Mt RK, regolith properties seem not to be particularly important. Although the ERT survey provided evidence of bedrock variability, this was also reflected in regolith thickness (Pawlik and Kasprzak 2012), the area with pit-and-mound topography is spread over the entire hillslope (Pawlik et al. 2013) and not limited to any particular, narrow altitude belt. Furthermore, the same fine-grained, mudstone-dominated complex crops out on adjacent slopes which do not bear evidence of large-scale wind-related surface disturbance. Finally, the 2007 Kyrill event, which devastated large tracts of forest in the Sudetes (Pawlik et al. 2016), had no effect on Mt RK. Only single trees have been uprooted within the research site over the last few tens of years, probably as random effects of various events.

In a similar way, slope factor appears of negligible importance. Firstly, pits and mounds cover the entire slope, including the gently convex upper part and steep mid-slope section (Pawlik et al. 2013). Secondly, adjacent slopes are steep too but do not have a similar type of microtopography, suggesting that the event responsible for forest fall on the study site left the vicinity relatively unscathed.

Thus, the biotic factor remains the key one. Various sources reviewed above suggest that a spruce mono-stand was affected by the wind event in the 1930s. In the Sudetes, spruce communities are particularly vulnerable to strong wind, especially planted ones (Pawlik et al. 2016). The subsequent change to beech community increased forest resistance and overall hillslope stability. Consequently, although the windfall event itself was a natural one, there is clear anthropic component in the cause-and-effect chain, related to forest management.

Pit-and-mound topography at Mt RK is approximately 80 years old and still well visible, despite likely forestry operations and log removal after the strong wind event. It is possible that some pit-and-mound associations are older, as suggested by both the subdued topography and more advanced pedogenesis at these forms, and indirectly confirmed by ages of sycamore maples. Results from other regions suggest that pit-and-mound topography may persists for 200–500 years (Šamonil et al. 2010a). In some cases radiocarbon dating of charcoals revealed ages of even 4,000–6,000 years (Šamonil et al. 2014).

Conclusions

Pit-and-mound topography of forest floor is usually analysed in the context of contemporary environments and processes and often documented shortly after the catastrophic wind event which created this specific type of relief. However, pit-and-mound relief at many localities is a relict and has a history, whose recognition may provide valuable evidence of causes, interactions and relationships between various abiotic and biotic factors. The case of Mt RK is one such example, where the history of forest floor topography and disturbance imposed by various factors can be traced back to at least the 1930s. To reconstruct the past and extend our understanding of pit-and-mound topography, its origin and impact on subsequent environmental change, various complementary approaches should be used, and this study demonstrates the value of different proxies if these are considered together. To decipher the history of pit-and-mound associations, dendrochronology and historical map analysis proved most useful and provided vital information that allowed us to link forest and surface disturbance with a particular event of strong wind. Using these sources as a reference data, we attempted to date pit-and-mound microrelief by means of soil properties (organic carbon content, iron forms). This was only partly successful. Although the young age of pits and mounds is evident, the actual age inferred from soil properties was underestimated by a few tens of years. On the other hand, soil analysis coupled with landform recognition allowed us to identify individual pit-and-mound associations which likely predate the origin of the main pit-and-mound field. Looking at soils in detail, we were able to identify different evolutionary pathways of pedogenesis, consistent with those reported in the literature. Evaluation of the factors potentially controlling the propensity to originate pit-and-mound microrelief led to the conclusion that type of forest is a far more important variable than local abiotic factors of bedrock geology, regolith characteristics and slope inclination. This, in turn, can be easily controlled by forest management practices through which windfall-prone or windfall-resistant communities may be introduced. In the particular case of the wind calamity on Mt Rogowa Kopa in the 1930s an anthropic factor appears crucial.

Acknowledgements

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