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Original Research

Water Repellency of Mountain Forest Soils in Relation to Impact of the Katabatic Windstorm and Subsequent Management Practices

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Abstract

Even though massive winds are significant disturbing factors for forest ecosystems, studies assessing topsoil properties in relation to wind-induced changes in forest floor and, specifically, works dealing with soil water repellency are lacking. On the other hand, the majority of works aimed at the wettability of soil have been carried out on soils from arid or semiarid climatic regions. Besides that, much less attention has been dedicated to soil water repellency in boreal-temperate regions and mountainous areas in particular. Here we report on water repellency of topsoil in mountainous region of the High Tatras of northern Slovakia (central Europe), where katabatic windstorm have blown down app. 12,500 hectares of forest canopy. Different management practices applied on windblown areas together with fire impact have resulted in four types of sites in the area: harvested, reference, left on self-recovery and struck by wild-fire. In order to cover the diversity of topsoil conditions, samples were taken at four representative sites. Results of WDPT and MED measurements show that a great portion of samples exhibited considerable degree of water repellency. It was found that there are significant differences in actual water repellency and field water contents between particular groups of samples taken at individual sites. Results of multiple regression analysis showed that water repellence of topsoil material is significantly controlled by water and organic carbon contents. Besides, for fire-unaffected soils it was found that the degree of water repellence is closely related to detected values of soil reaction as well. Explained portions of WDPT and MED variances ranged from 45 up to 72%.

Keywords: topsoil properties, water repellency, katabatic windstorm, acidic humus

Introduction

A temporary condition of soil surface closely related to SOM quality and quantity, wettability of soil material is sensitive to environmental conditions and might be easily affected by changes in such conditions. Significant abiotic factors and variables affecting this phenomenon are often climate related. Soil water content and its change have been stressed perhaps the most frequently as important factor in a number of studies. In general, soil is more prone to water repellency development at lower and less at higher water content [e.g. 1, 2]. Therefore, water repellence has been reported to occur especially during summer droughts, whereas during wet periods its occurrence is rather ceased

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by high water contents. One of the aspects of the soil moisture and water repellency relationship is critical water content. It was found that susceptibility of soil material to become water repellent is related to certain critical water content below which soil exhibits water repellency and above which is wettable [1, 3]. However, this level of soil moisture is often not perceived as a certain exact value of water content. Usually there is the interval of moisture - transition zone, in which soil material may exhibit either water repellent or wettable properties.

In order to establish the relationship between soil water repellency and other soil characteristics the correlation and regression analyses have been performed on a population of soil samples with various origins, taken at variable scales. The authors have come to different conclusions, when assessing the significance of individual soil properties as possible predictors, which would explain the variability of soil wettability sufficiently. Whereas the majority of studies confirmed predictive power of soil water content [e.g. 1, 3], the findings concerning the effect of other soil characteristics on water repellency, such soil organic matter (SOM), carbon (SOC) contents or textural composition vary between studies. For example, Johnson et al. [4] did not find any relationship between detected water repellency of samples and contents of SOM or their textural composition in a study aimed at the temporal and spatial variability of water repellency. Similarly, Dekker and Ritsema [5] found an insignificant relationship between SOM content and potential water repellency. Doerr et al. [6] reported only poor predictive power of SOM, textural composition and specific water content in relation to water repellency, whereas type of land use and moisture level bellow which repellency might occur proved to be more reliable predictors. Scott [7] explained 46% of variability of CST (critical surface tension) and 27% of ACA (apparent contact angle) values by variability of SOM and soil texture. Täumer et al. [3] suggest that soil water repellency is significantly controlled by soil moisture and organic matter content. This was found in a plot scale study aimed at water repellency distribution at a site which served for the application of untreated wastewater. Moral Garcia et al. [8] reported a positive relationship between water repellency and organic matter content of topsoil samples taken in southern Spain. Zhao et al. [9] elucidated a high portion of WDPT variability ($R^2 = 0.79$) by means of multiple regression analysis using hydraulic conductivity and content of silt fraction as predictive soil variables. In the same study a great portion of spatial variable hydraulic conductivity was explained by variation of detected WDPT values and soil organic carbon (SOC) contents ($R^2 = 0.77$).

Forest ecosystems have been affected and sculpted by wildfires and fierce winds throughout history in various forested landscapes of the world. Whereas changes of soil wettability due to impact of fire have been discussed in many studies, much less data (if at all) exists concerning a possible link between windstorm impacts on forest ecosystems and potential development of soil water repellency. Moreover, from the perspective of global occurrence of soil water repellency phenomenon, the majority of works assessing soil wettability were carried out in arid or semiarid regions [e.g. 7, 10, 11]. On the other hand, studies dealing with the occurrence of soil water repellency in temperate or more humid climatic regions were carried out mainly on coarse textured (sandy) soils [3, 12] or those situated in coastal areas at low altitude [1, 13].

In order to fill this gap we examined the conditions of soil surface horizon and particularly its wettability in the mountain region of High Tatras, in northern Slovakia (Central Europe) where a bora-katabatic windstorm swept down app. 12,500 hectares of forest canopy on 19.11.2004. Topsoil properties, e.g. moisture, organic matter content, textural composition or wettability are crucial environmental factors because they are directly related to water transfer mechanisms [14] such as surface runoff, erosion, or plant growth, particularly in a windstorm or fire-affected area. The purpose of this study was to evaluate the occurrence of water repellency of soil surface at four experimental sites in the High Tatras region and its relation to selected soil properties (water and soil organic carbon contents, soil reaction and textural composition).

Materials and Methods

Site Description and Soil Sampling

The sampling process was carried out at the end of July 2006. The date was selected in accordance with meteoro-

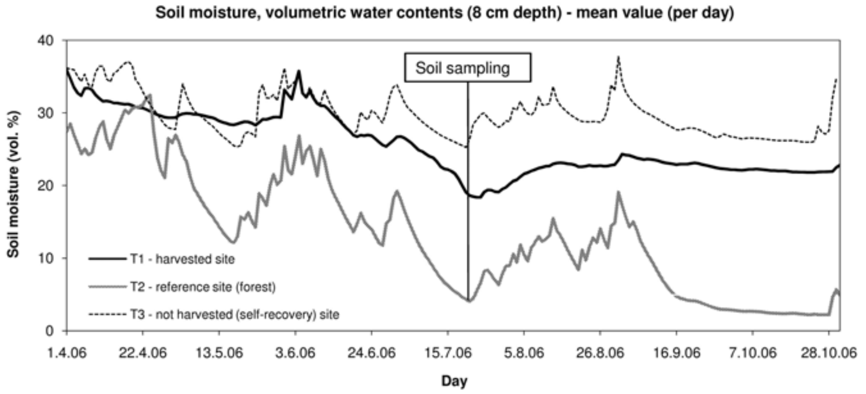

Fig. 1. Samples were taken in summer in a relatively dry weather period, when soil is prone to water repellency development.

logical conditions and events which are favourable for water repellency development, and significant from the point of its hydrological response. Soil water repellency have been reported to occur during prolonged droughts, usually in the summer, when soil water content tends to decrease below certain levels (Fig. 1) and soil is more prone for water repellency development [1]. During summer, dry periods are often followed by storms or heavy rain events, which might cause significant hydrological consequences (increased surface runoff, erosion) [11 ,15]. In addition, fire-induced soil water repellency can have a serious impact on re-establishing a plant community in a particular area [16].

For the monitoring purpose of windblown aftermath, four experimental sites were established by the TANAP (Tatra National Park) research station, and soil samples were taken from these. The sites which were monitored (Fig. 2) comprise one reference and three calamity sites, from which two differ from the point of applied management practices and the third is situated within the area which was stroked by (wild) fire after the windblown impact in July/August 2005. In order to cover spatial variability of soil properties, in the case of each experimental site from 400 m^2 area, 15 samples of topsoil (depth interval 0-5 cm) were taken at random. The studied soil was developed on quaternary moraine gravel layer and classified as Dystric Cambisol [17].

1. The site denoted as T1 is situated within the area where wood mass of fallen and broken trees was harvested. Coordinates (WGS 84) of the site are: N 49°07′12.0″, E 20°09′47.5″ (altitude 1,043 m above sea level). The mean annual temperature is 4.9°C (with mean monthly maxima of 14.6 and minima of -5.2°C).
2. T2 is a reference site located under a canopy of spruce forest (*Picea abies*, L.) at 1221 m above sea level. Coordinates of the site are: N 49°07′17.5″; E 20°06′16.4″. The mean annual temperature is 4.3°C (with mean monthly maxima of 13.7 and minima of -5.1°C). Mean annual precipitation is 864 mm.
3. Experimental site T3, termed also as “self-recovery,” is situated within the area where felled wood of the trees was left without any human intervention. Coordinates of the site are: N 49°09′60.5″, E 20°15′14.8″ (1,067 m above sea level). The mean annual temperature is 5.3°C (with mean monthly maxima of 15.2 and minima of -4.9°C). Mean annual precipitation is 833 mm.
4. T4 site is located within the area where wood mass was harvested and which at the same time was struck by wildfire on 30.7.2005. Due to windy conditions, fire spread onto an area of app. 250 ha and burned app. 18,000 m^3 of wood. Coordinates of the site are: N 49°07′82.7″, E 20°11′83.2″ (1,016 m above sea level). The mean annual temperature is 4.7°C (with mean monthly maxima of 14.4 and minima of -5.6°C). Mean annual precipitation is 931 mm.

Chemical and Physical Soil Properties

Samples were air-dried at 22 ± 2°C (to constant weight) and passed through a 2 mm sieve before analysis. Soil water content of field-moist (w_F) and also air-dried (w_L) samples was determined gravimetrically and expressed as mass wetness ratio (before and after drying at 105°C). Soil pH values were determined by potentiometric method in distilled water using a soil/solution ratio of 1:2.5. Soil organic carbon (SOC) content was determined by oxidation

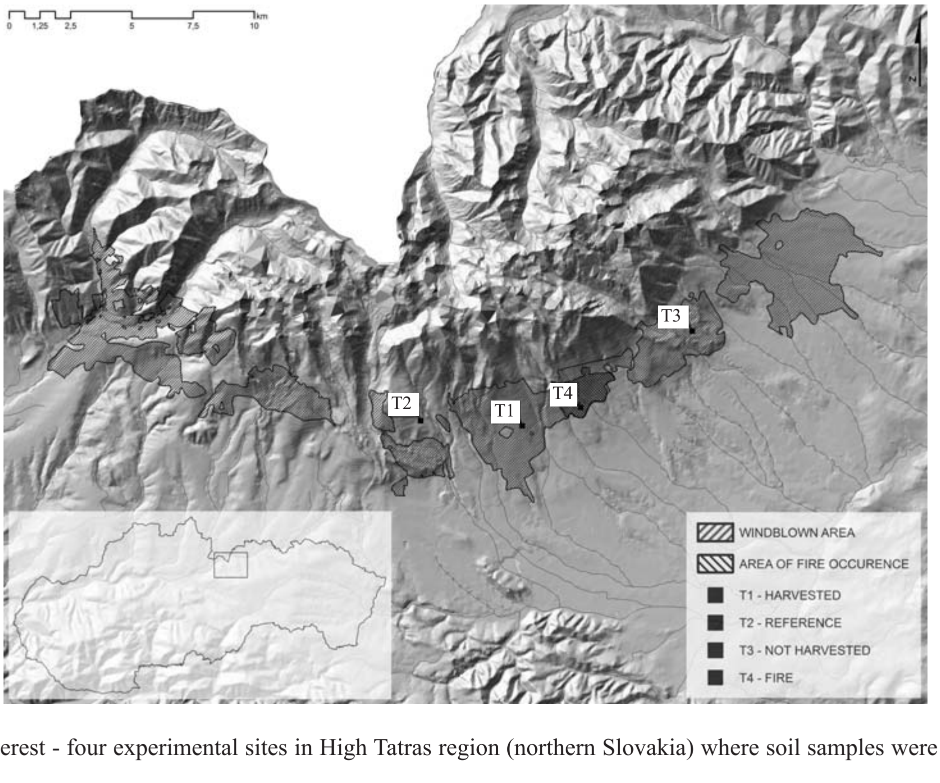

Fig. 2. Area of interest - four experimental sites in High Tatras region (northern Slovakia) where soil samples were taken.

Table 1. Descriptive statistics of measured soil properties concerning a whole set of 60 samples.

	w_F (%)	w_L (%)	Log WDPT$_F$ (s)	Log WDPT$_L$ (s)	MED (mol l^{-1})	SOC (%)	pH	Sand (%)	Silt (%)	Clay (%)
mean	48.50	3.87	1.93	2.59	1.84	7.04	3.70	66.37	24.08	9.55
median	44.62	3.71	1.65	2.95	2.11	7.10	3.74	65.90	24.60	9.68
s.d.	17.47	0.84	1.92	1.46	1.19	2.11	0.22	5.68	4.43	1.97
m.d.	13.10	0.67	1.93	2.59	1.05	1.68	0.18	4.42	3.43	1.55
c.v.	0.36	0.22	1.00	0.57	0.65	0.30	0.06	0.09	0.18	0.21
range	90.95	3.96	4.64	4.64	3.96	9.90	0.96	25.94	20.61	10.49
min.	16.48	2.25	0.00	0.00	0.00	3.00	3.21	55.59	11.88	4.90
max.	107.44	6.21	4.64	4.64	3.96	12.90	4.17	81.53	32.49	15.38

s.d. - standard deviation; m.d. - mean deviation; c.v. - coefficient of variation

with $K_2Cr_2O_7$-H_2SO_4 and titration of non-reduced dichromate. Texture of the soil samples was determined by mechanical analysis (pipette method). Contents of sand (2-0.05), silt (0.05-0.002) and clay (< 0.002 mm) fractions were measured and results were classified according to USDA-FAO texture triangle [18].

Soil Water Repellency

Persistence of water repellency was assessed by the widely used water drop penetration time (WDPT) test [19]. Similarly to Dekker et al. [1] or Doerr et al. [6] the measurements were carried out on soil samples at field water content (WDPT$_F$ - actual water repellency) and after drying at 22 ± 2°C to constant weight (WDPT$_L$ - potential water repellency). Samples were placed in Petri dishes and three drops of distilled water (0.05 ml) were placed onto the surface of soil sample using medicinal dropper and actual time required for complete penetration of the droplet was recorded. In order to reduce evaporation, Petri dishes were covered when testing. The average of three WDPT values was used to classify a sample. The following classes of water repellency persistence [19] were distinguished: wettable (< 5s), slightly water repellent (5-60 s), strongly water repellent (60-600 s), severely water repellent (600-3,600 s), extremely water repellent (> 3,600 s). The upper measured time interval was 43,200 s (12h).

For assessment of water repellency severity, the MED (molarity of an ethanol droplet) test was performed [19]. Standardized solutions of ethanol in water were used, ranging from 0.17 mol l^{-1} to 7.49 mol l^{-1} (with 1 vol.% increments). Drops (0.05 ml) were applied in order of increasing concentration until penetration occurred within 3 s [19]. The MED test was performed on air-dried samples only, to avoid dilution effects of the ethanol solution in the droplets by the water contained in field moist samples. Results of testing were classified as follows [19]: wettable (0-0.85), slightly (0.85-1.45), moderately (1.45-2.22), strongly (2.22-3.07), very strongly (3.07-6.14), extremely water repellent (> 6.14 mol l^{-1}) soil. It is worth noting that limits of WDPT and particularly MED classifications are often varying among authors, and therefore particular classes not always express environmental or hydrological importance of detected degree of water repellence [20].

Statistical Assessment

Before any statistical processing of values, normality of their distribution was tested by the Kolmogorov-Smirnov test. Parameters of descriptive statistics (mean, median, standard deviation, mean deviation, coefficient of variation) were calculated considering a complete statistical population (60 cases) and also for each of four groups of samples (experimental sites T1, T2, T3 and T4), respectively (each consisting of 15 cases). In order to find whether katabatic wind impact and related subsequent events (different management practices applied, fire occurrence) affected selected properties of topsoil significantly, differences between WDPT$_F$ and w_F results detected for T1, T2, T3 and T4 group of samples, respectively, were assessed by a t-test in which groups of values corresponding to particular variables (WDPT$_F$ and w_F) were treated as independent.

Pearson's coefficients of correlation were calculated for couples of measured soil properties. There is a reasonable assumption that degree of soil water repellency depends on more than one soil variable. Soil water and organic matter contents, its textural composition or soil reaction are properties which have been reported to be partaking on soil wettability [e.g. 21, 6]. Therefore, the multiple regression analysis was performed using these particular variables as possible predictors of water repellency. Detected values of mass wetness, SOC content, soil reaction and content of individual textural fractions were used in regression analysis as independent variables ($X_1,\ldots, X_n$) in order to explain variability observed in WDPT (moist and air dried samples) and MED values, respectively, which were considered as dependent (Y). The criterion of the least squares was applied in regression analysis. In general, the function of simple and also multiple regression can by assumed as:

$$y = f(x_1,...,x_n; b_0, b_1,..., b_n) \quad (1)$$

...where $x_1, \ldots, x_n$ are values of particular explanatory variables; $b_1, \ldots, b_n$ are regression coefficients of variables that approximate the shape of the function and b_0 is the intercept. Here, for purposes of multiple regression, we consider the function *f* as the sum of weighed terms (selected soil variables) or its simple transformations (e.g. $Log\,x$, $\sqrt{x}$, x^n, x_1/x_2). Significance of partial regression coefficients b_n was assessed by testing the $t=b_n/se(b_n)$ value according to Student probability distribution (two-tailed) at particular degrees of freedom (v). If the error probability value was less than 0.05, the regression coefficient was considered to be taking on the shape of a particular function significantly. For each of the obtained equations and particular coefficients of multiple determination (R^2), the *F* value were calculated as follows:

$$F = [R^2/k]/[(1 - R^2)/(n - k - 1)] \quad (2)$$

...where n is number of cases, k is number of terms in the equation and expression ($n - k - 1$) signifies degrees of freedom (v). Calculated F value was tested according to Fisher-Snedecor probability distribution at particular degrees of freedom (v) and expressed as error probability.

Results and Discussion

Descriptive statistics for the whole set of 60 samples are presented in Table 1. Coefficient of variation, standard and mean deviation values suggest considerable variability of soil water contents and water repellency. In the case of field moisture (w_F) mass wetness values ranged from 16.5 to 107.4%. Substantially less variables were the water contents detected for air-dried samples (w_L). Values of SOC contents exhibited certain variability as well, but less distinct in comparison to detected field moisture contents, WDPT or MED values. SOC contents ranged from 3.0 to 12.9%. Soil reaction was strongly acidic (3.21-4.08) in the majority of samples, which may be associated with the granite nature of the moraine parent material, relatively wet and cool climatic conditions and the vegetation community. From 60 soil samples, 56 were classified as sandy loam and in 4 cases the soils were classified as loamy sand according USDA-FAO texture triangle [18]. Except for WDPT data ($WDPT_F$, $WDPT_L$) which are discussed in the following section obtained values of other measured soil properties obeyed the criteria for normality of their distribution.

Soil Water Repellency

As well as in case of other studies with similar character [e.g. 4, 13], we also experienced high spatial variability in values of WDPT and less in MED testing. Being related to different aspects of soil water repellency, the results of these two methods may differ. WDPT reflect the stability of water repellecy and MED value rather than its actual severity [22].

WDPT Test

Within 60 observations, values ranged from 1 to 43,200 seconds (actual and also potential WDPT). Soil samples, according to WDPT measurements, performed on samples at their field water content, were wettable in 27 cases and extremely water repellent in 21. Other samples were classified as strongly (7), slightly (3) and severely (2) water repellent. Similarly, as it was observed in the case of Täumer et al. [3], a histogram of detected $WDPT_F$ values corresponding to field-moist samples suggests slightly bimodal distribution (not shown). The drying process (to constant weight) resulted in certain changes of water repellency persistence with less impact on extremely water repellent class. WDPT of soil samples, classified in moist state as extremely water repellent, decreased in 14 cases (three samples dropped into lower WDPT class after drying), increased in 4 and in 3 cases exceeded 43,200 seconds before as well as after the drying phase. From the other 41 soils classified within less water repellent categories, WDPT of 40 increased after drying. After drying, the number of severely (13), slightly (11) and strongly (9) water repellent samples was higher in comparison to field-moist repellency. Overall, the shift in WDPT results (either positive or negative) was observed in 55 cases, but 29 samples remained within the same category of used WDPT classification. The increase of soil water repellency was observed in 40 cases, 30 of which were accompanied by change of WDPT class in at least by one category.

Drying at room temperature (22 ± 2°C) caused a certain increase of soil water repellency in the case of initially wettable samples, whereas a decrease of WDPT observed after drying refers particularly to initially water repellent samples. Similar findings were presented by Dekker et al. [1] and also Bayer and Schaumann [21]. Here both groups of values showed a high degree of correlation ($r = 0.91$). However, the statistical assessment of WDPT values is getting difficult when values exceed the highest measured time interval (in our case 43,200 seconds). For these, the actual time of droplet infiltration remained unknown and rather than infiltration of the droplet its evaporation is often observed. For the purpose of computing various statistics used and presented in this study we used 43,200 s as actual WDPT in the case of time intervals exceeding this threshold value.

MED Test

MED values ranged from 0 to 3.96 mol l^{-1}. Although certain scales for MED-testing were proposed [19], molarities of particular ethanol droplets are often presented without any classification as well [e.g. 31]. According to the scale suggested by Doerr [19], it is possible to classify samples as follows: wettable (18 samples), slightly (8), moderately (8), strongly (15) and very strongly water repellent (11 samples). MED values sufficiently obeyed the criteria for normal distribution and no further transformation onto Log scale was needed. In contrast to the WDPT test, the advantage of MED resides in its suitability also for extreme water repellent samples, the case for which is that performing WDPT

Table 2. Matrix of probability values obtained via t-test, describing the significance of difference beetwen WDPT_F values (a) and field water contents - w_F (b) detected for individual experimental sites.

		T1	T2	T3	T4
a	T1	1			
	T2	0.002**	1		
	T3	0.028*	$1.73\ 10^{-9}$***	1	
	T4	0.087	0.190	$4.90\ 10^{-9}$***	1
b	T1	1			
	T2	0.786	1		
	T3	0.002**	0.003**	1	
	T4	0.076	0.101	0.035*	1

*, **, *** indicate statistical significance at the 0.05, 0.01, and 0.001 level

is too laborious and less precise due to evaporation of the droplet. However, for the MED method it was found disadvantageous that dilution effects by water present in the samples are probable when performing measurements on moist field samples. Results of MED test exhibit high degree of correlation with WDPT performed after drying samples to constant weight ($r = 0.96$) and less, but still remarkably significant, with WDPT performed at field water content ($r = 0.90$).

Wettability of Surface Horizon Related to Measured Soil Properties at Four Experimental Sites

Results of t-test showed that there is a significant difference in actual water repellency and field moisture contents between particular groups of samples taken at four experimental sites. Samples taken at T3 (self-recovery) site, where necromass of fallen and uprooted trees was left without intervention, contained in field conditions substantial higher amounts of water (w_F) in comparison to topsoil samples taken at each of the other experimental sites, and hence exhibited only negligible levels of actual water repellency (WDPT_F - Table 2).

Harvested Sites

Particular statistics describing each of four sets of samples representing soil properties at particular sites are presented in Table 3. T1 and T4 are sites situated within the windblown area. These two are similar from the point of applied management practices (harvesting of the broken and uprooted trees), character of microrelief and vegetation cover. Soil samples from the T4 site exhibited higher pH values (3.72-4.17), which is related to ash production during fire and its subsequent input into the topsoil. However, in comparison to fire unaffected samples the increase of soil reaction was not very distinct. Although fire spread onto a relative large area, its intensity remains doubtful because parameters possibly demonstrating it, such as temperatures reached, are missing. Only app. 3 cm (mean value calculated from 15 observations) thick layer of charred plant debris resulting from an incomplete combustion and pH values detected one year after the impact of fire suggest rather low to moderate fire intensity.

Besides soil reaction sites, T1 and T4 differ in soil organic carbon content. Average and median SOC contents at the T1 site were markedly lower in comparison to SOC contents detected in topsoil samples at three other sites. Besides spatial variability and sample heterogeneity, detected low SOC contents might also originate from sampling inaccuracy (mixing of A/B and A horizon). Higher average and median values of SOC content at T4 might be attributed to additional input of partially burned plant material, as this has been reported [23]. Soil samples from the experimental site within the area of fire occurrence showed relatively high degree of water repellence according to WDPT, as well as MED results. The increase of water repellence after the impact of (wild) fire has been observed numerous times by various authors [e.g. 16, 24]. Results of t-test, however, suggest that actual water repellency at T4 (windblown - harvested with fire occurence) is not significantly different from T1 (windblown - harvested) and T2 (reference) experimental sites.

Not Harvested (Self-Recovery) Site

Soil samples from T3 experimental site were significantly different from all other samples, mainly in soil water contents and water repellency. Complete wettability or only slight water repellency was confirmed by WDPT and MED tests not only for field moist samples but also for samples dried to constant weight (Tables 1 and 3). WDPT performed at field water content showed that 13 from 15 samples of surface horizon did not exhibit water repellency at all, probably due to the high level of soil moisture (mean = 63.04; median = 60.88% of weight). Drying process at room temperature induced only limited increase of soil water repellency in soil samples. The majority of soils (11 from 13) that were classified as wettable in field-moist state developed only slight water repellency (9) or remained within the wettable category after drying (2). Higher field water contents and low water repellency detected in the case of T3 experimental site are, at least partially, caused by applied management practices in the area. By shading of soil surface, wood mass of fallen trees is impeding the evaporation, and thereby partially preserving the moist conditions in the area. In contrast to the reference site, uprooted and broken trees without transpiration proceeding are significantly contributing to relatively humid microclimatic conditions in the area. A greater degree of water retention in surface horizon throughout the summer-autumn period at T3 in comparison to other experimental sites (T2 and T1) is depicted in Fig. 2. This, however, refers only to a one-year time period in which soil samples were taken. Subsequent desiccation of wood necromass might, for example, increase fire risk in the area due to accumulation of fuel material.

Reference Site

According to WDPT and MED results the greatest degree of water repellency was detected for soils situated within the area where the forest canopy remained unaffected by the impact of a katabatic windstorm. The difference in field moisture level between forest reference site and harvested sites was found to be insignificant during the relatively dry summer period when soil samples were taken. At field water content (w_F) ranging from 19.8 up to 60% (Table 3), only in the case of one soil sample was its wettability detected (WDPT). Nine samples exhibited time intervals of droplet penetration exceeding the limit for extreme water repellency (3,600s). The other 5 samples were classified as severely (2) and strongly (3) water repellent. Drying at room temperature resulted mainly in severe (6) and extreme (7 samples) water repellency. Soils from the reference site showed the highest mean and median values (Table 3), for not only WDPT and MED values but also for SOC and sand fraction contents. At the same time, these samples exhibited the most acidic character (pH in H_2O) in comparison to T1, T3 and T4 samples.

Table 3. Descriptive statistics for measured soil properties detected at individual experimental sites, respectively.

	w_F (%)	w_L (%)	Log WDPT$_F$ (s)	Log WDPT$_L$ (s)	MED (mol l^{-1})	SOC (%)	pH	Sand (%)	Silt (%)	Clay (%)
T1 (harvested site)										
mean	40.51	3.65	1.41	2.36	1.48	5.37	3.78	65.62	24.65	9.73
median	39.16	3.73	0.10	2.24	1.40	4.60	3.75	65.26	24.65	9.92
s.d.	13.43	0.77	1.92	1.55	1.05	1.91	0.13	3.74	3.40	1.60
m.d.	10.48	0.58	1.65	1.27	0.88	1.64	0.10	3.10	2.35	1.33
c.v.	0.33	0.21	1.36	0.66	0.71	0.36	0.04	0.06	0.14	0.16
range	50.32	2.91	4.64	4.64	3.21	5.40	0.52	11.31	12.48	5.14
T2 (reference site)										
mean	41.76	3.95	3.45	3.53	2.86	8.01	3.50	70.16	21.08	8.76
median	42.12	3.73	3.63	3.44	2.84	8.10	3.52	68.63	22.93	8.93
s.d.	11.65	0.65	1.37	1.10	0.93	2.28	0.20	6.88	4.87	2.33
m.d.	9.24	0.50	1.06	0.80	0.60	1.79	0.16	5.79	4.20	2.04
c.v.	0.28	0.16	0.40	0.31	0.32	0.28	0.06	0.10	0.23	0.27
range	38.27	2.56	5.29	4.23	3.79	7.50	0.56	21.02	15.82	7.16
T3 (not harvested site)										
mean	63.04	3.39	0.21	1.32	0.84	7.37	3.60	66.70	24.31	8.99
median	60.88	3.23	0.00	1.09	0.52	7.20	3.58	66.64	25.13	8.95
s.d.	22.61	0.80	0.56	0.82	0.69	1.45	0.15	5.47	4.72	1.32
m.d.	16.82	0.38	0.36	0.61	0.54	1.22	0.13	4.48	4.16	1.01
c.v.	0.36	0.24	2.70	0.62	0.82	0.20	0.04	0.08	0.19	0.15
range	90.95	3.35	1.86	2.57	2.13	4.40	0.48	18.29	14.52	5.41
T4 (harvested site affected by fire)										
mean	48.70	4.51	2.59	3.05	2.17	7.41	3.91	62.99	26.28	10.73
median	43.66	4.29	3.63	3.59	2.48	7.20	3.90	62.79	25.91	10.37
s.d.	10.75	0.73	1.84	1.38	1.03	1.89	0.11	4.05	3.15	2.02
m.d.	9.14	0.57	1.66	1.14	0.81	1.43	0.07	3.50	2.64	1.51
c.v.	0.22	0.16	0.71	0.45	0.48	0.26	0.03	0.06	0.12	0.19
range	37.09	2.83	4.64	4.33	3.04	7.20	0.45	13.48	9.92	7.70

s.d. - standard deviation; m.d. - mean deviation; c.v. - coefficient of variation

Table 4. Coefficients of correlation (*r*) presented in the form of correlation matrix for measured soil variables.

	Log WDPT$_F$	Log WDPT$_L$	MED	w_F	w_L	SOC	pH	Sand	Silt	Clay
a. correlation matrix for n = 60										
Log WDPT$_F$	1									
Log WDPT$_L$	0.91***	1								
MED	0.90***	0.96***	1							
w_F	-0.57***	-0.49***	-0.50***	1						
w_L	0.03	0.13	0.18	0.06	1					
SOC	0.11	0.20	0.26*	0.30*	0.50***	1				
pH	-0.07	-0.07	-0.19	-0.14	0.19	-0.38**	1			
Sand	0.04	0.04	0.10	-0.13	0.09	0.01	-0.03	1		
Silt	-0.08	-0.09	-0.14	0.18	-0.12	0.03	0.01	-0.95***	1	
Clay	0.08	0.06	0.05	-0.05	0.03	-0.08	0.08	-0.74***	0.50***	1
b. *r* values for selected couples of soil variables after exclusion of fire affected samples (n = 45)										
pH	-0.35*	-0.32*	-0.43**	-0.15	0.00	-0.58***	1	0.26	-0.26	-0.16

*, **, *** indicate statistical significance at the 0.05, 0.01, and 0.001 level

Critical Water Content

WDPT results and associated soil moisture values revealed the relatively broad range of field water content within which samples exhibited wettable as well as water repellent properties. The highest mass wetness value of the water repellent soil sample (WDPT ≥ 60s) was 59% and the lowest of the wettable (WDPT ≤ 5s) was 26% (Fig. 3). In studies where water repellency was assessed from the point of critical water content [e.g. 1, 3, 12, 25], usually more narrowed intervals of soil moisture corresponding to transition zone have been presented in comparison to results reported in this paper. Nevertheless, from Fig. 3 it follows that water content is probably not the only parameter of soil controlling spatial variability of soil wettability, especially within the limits of the transition zone. Authors of studies assessing effects of various soil characteristics on soil wettability reported that higher degrees of water repellence might be associated with higher amounts of soil organic matter [3], a preponderance of sand fraction in textural composition [26] and/or lower soil pH values [21 ,27]. Some of their findings are in accordance with the results obtained here. It is possible that the relatively broad extent of the transition zone detected in this study might be, apart from a change of soil water content, positively affected by variance of other properties of soil, especially organic matter (carbon) content but possibly also soil reaction and/or textural composition.

Simple Correlation and Regression Analysis

Coefficients of correlation are presented in the form of correlation matrix (Table 4). Water repellency of field moist samples (WDPT$_F$) was correlated negatively with field water content (-0.57). The relation is visualized also in Fig. 3. Water repellency values of air-dried samples (WDPT$_L$) showed similarly high (but less prominent than in case of field-moist samples) negative correlation with field moisture (0.49). Negative correlation (-0.50) was observed also between field water content and MED results. The fact that WDPT (for moist and also dry samples) as well as MED values showed similar, negative correlation with field water content, suggesting the importance of initial moisture level, and hence a whole water regime of soil at particular stand, for development of water repellency not only in the case of field-moist samples, but also after their drying in relatively moderate conditions (e.g. 20-30°C). Correlation between WDPT data and contents of organic carbon was found to be insignificant similarly as it was in the case of water repellency and contents of individual textural fractions. Significant positive correlation between soil organic carbon and water repellency was detected only when MED results (0.26) were used for calculating the r value.

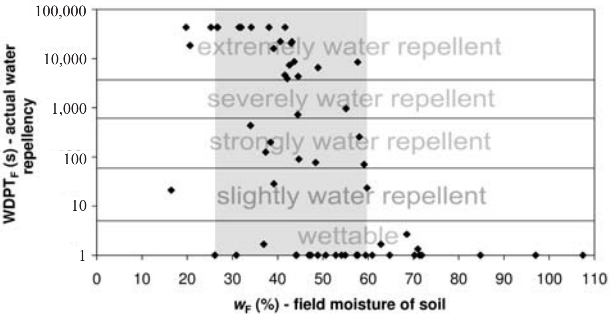

Fig. 3. Results of field moist WDPT testing (WDPT$_F$) plotted against soil moisture values with transition zone of soil water content depicted.

Table 5. Equations obtained by multiple regression analysis and parameters characterizing particular regression models (R^2 - coefficient of multiple determination, F - observed value of the F statistic, P - error probability value of F statistics, *d.f.* - degrees of freedom) proposed for explaining of $\mathrm{WDPT_F}$ (a), $\mathrm{WDPT_L}$ (b) and MED (c) variances.

	R^2	F	P	*d.f.*
a. *Regression Equation*				
1. $\mathrm{Log\ WDPT_F} = 1.36\ 10^{-3}\ w_F^2 - 0.23\ w_F + 0.28\ \mathrm{SOC} - 3.73\ \mathrm{pH} + 20.86$	0.72	24.97	$1.20\ 10^{-17}$	38
2. $\mathrm{Log\ WDPT_F} = - 9.00\ \mathrm{Log}\ w_F + 0.25\ \mathrm{SOC} - 3.67\ \mathrm{pH} + 28.15$	0.69	28.38	$4.48\ 10^{-19}$	39
3. $\mathrm{Log\ WDPT_F} = - 0.07 w_F + 0.18\ \mathrm{SOC} - 3.81\ \mathrm{pH} + 17.61$	0.59	19.04	$5.83\ 10^{-16}$	39
b. *Regression Equation*				
4. $\mathrm{Log\ WDPT_L} = 1.22\ 10^{-3} w_F^2 - 0.19\ w_F + 0.27\ \mathrm{SOC} - 2.14\ \mathrm{pH} + 14.33$	0.62	15.62	$3.93\ 10^{-14}$	38
5. $\mathrm{Log\ WDPT_L} = - 6.24\ \mathrm{Log}\ w_F + 0.24\ \mathrm{SOC} - 2.10\ \mathrm{pH} + 18.73$	0.54	15.30	$2.63\ 10^{-14}$	39
6. $\mathrm{Log\ WDPT_L} = - 0.05\ w_F + 0.18\ \mathrm{SOC} - 2.21\ \mathrm{pH} + 11.42$	0.45	10.56	$1.33\ 10^{-11}$	39
c. *Regression Equation*				
7. $\mathrm{MED} = 8.35\ 10^{-4}\ w_F^2 - 0.14\ w_F + 0.22\ \mathrm{SOC} - 2.36\ \mathrm{pH} + 13.41$	0.68	19.89	$6.38\ 10^{-16}$	38
8. $\mathrm{MED} = -5.31\ \mathrm{Log}\ w_F - 2.33\ \mathrm{pH} + 0.20\ \mathrm{SOC} + 17.63$	0.62	21.40	$7.34\ 10^{-17}$	39
9. $\mathrm{MED} = -0.04\ w_F + 0.16\ \mathrm{SOC} - 2.41\ \mathrm{pH} + 11.42$	0.56	16.61	$6.39\ 10^{-15}$	39

Considering simple regression, coefficients of determination (r^2) obtained by powering Pearson's coefficient of correlation (r) does not explain the relation between particular variables sufficiently, since it is related to linear relationship only. For example, Goebel et al. [28] and also Regalado and Ritter [29], reported that water repellency varies with soil water content nonlinearly. In this study applying linear, logarithmic or polynomial (quadratic) models in simple regression analysis resulted in relatively similar r^2 value. In general, the polynomial (quadratic) regression model provided slightly but not significantly higher r^2 value in comparison to linear, logarithmic or exponential.

It was found that applying simple correlations and regressions did not elucidate the relation between measured soil properties and water repellency sufficiently. This concerns mainly soil reaction and partially also organic carbon content. Besides already mentioned limitations of simple regression models, the effect of soil reaction on water repellency proved to be insignificant mainly due to relative high water repellency of fire-affected soil samples, which at the same time exhibited less acidic character due to ash inputs. After the exclusion of fire-affected samples, calculated r and r^2 values increased substantially (Table 4). It is worth noting that in the case of fire-unaffected topsoil samples, there is significant negative correlation between pH values and SOC contents. This is a relatively common observation for forest soils, especially for those situated under conifers where a decrease of pH value is driven by decomposition of accumulated organic residues originating from plant and microbial biomass, which are substantial sources of H^+. Because in these soils both variables (pH and SOC) are closely related to quality and quantity of soil organic matter, it is possible that they are affecting resulting degrees of soil water repellency considering fire-unaffected sites.

Multiple Regression Analysis

In order to explain spatial variability of water repellency, various forms of equations were tested. Transformations of independent explanatory variables through logarithms, square roots, ratios, power and cross products terms were applied in analysis according to theoretical assumptions and findings presented in works assessing the effect of particular variables on soil water repellency. Field moisture in general proved to be the explanatory variable with the highest predictive power in proposed equations. In this paper we present three types of equations which explain to a certain extent the variation of water repellency in the field. They differ in type of mathematical relation between soil moisture and wettability. Applying linear, logarithmic and quadratic trends in mass wetness soil water repellency relation resulted in a gradual increase of R^2 value (Table 5 and Fig. 4). Nonlinear variation of water repellency with change of soil water content was reported in a number of studies [21, 28]. Here logarithmic and quadratic models provided better results in comparison to linear, and we found them to be more appropriate for characterization of the relation between these two soil parameters. Degree of water repellence, was besides soil moisture, partially controlled also by organic carbon content, even though the relation between two variables appeared insignificant in the case of simple correlation and regression. The synergic effect of soil water and organic matter contents on resulting degrees of soil water repellency was reported by Täumer et al. [3], who showed that the extent of moisture interval in which samples exhibit both wettable as well as water-repelling characteristics, is significantly controlled by SOM content.

Content of individual textural fractions were shown to be of insignificant predictive power in proposed regression models. This can be associated with the identical nature of soil parent material at each experimental site, and relatively low spatial variability of textural composition. One may assume that field moisture, together with properties of soil organic matter, are the only parameters controlling spatial variation of soil wettability at sites directly, whereas factors such as character of relief, vegetation cover or applied practices in forest management affect water repellency indirectly through mentioned primary factors.

An interesting finding arose from the multiple regression analysis for water repellency data of air-dried samples. Besides field moisture (w_F), water content of air-dried samples (w_L) was successfully tested as a partial predictor in particular regression equations. In contrast to the negative effects of field moisture levels on WDPT and MED values, regression analysis showed that residual water content of air-dried samples affect degrees of soil water repellence positively. This positive effect of soil moisture, which can be observed within certain intervals of water content, is possible to associate with findings of authors exploring the relation of water repellency and soil moisture in detail. They reported that after maximum repellency is reached by lowering water content, further desiccation of soil re-increases its wettability [28, 30, 31]. Positive correlation of WDPT$_L$ and MED values with residual moisture of air-dried samples might be explained by lower surface energy of soil material when not enough water molecules are adsorbed on polar organic or even mineral surfaces to form a liquid film. Although these findings are in some sense similar to results observed here, the more definite evidence supporting described character of relation between water repellency and residual water content for studied soils is lacking. For example, it is possible that the positive relation between water repellency and residual water content actually reflects the fact that residual soil moisture is being positively correlated with SOC content (r = 0.50), which in turn affects the degree of water repellency positively. For these reasons, mass wetness of air-dried samples (w_L) was not included into final regression equations.

Selected regression equations attempting to explain the variability of WDPT and MED values for fire-unaffected soils, together with particular statistics, are presented in Table 5. In order to visualize the relation between results of multiple regression analysis and wetting behaviour observed in the field, Fig. 4 depicts predicted values of field water repellency as a function of observed data. In the scatter plots three types of regression models are presented. Individual models predicting actual water repellency are differing in type of applied relation between field moisture of soil and its actual water repellency (a - quadratic, b - logarithmic and c - linear). The proposed equations presented in Table 5 suggest similar trends of regression for all three measured variants of repellency (WDPT$_F$, WDPT$_L$ and MED). The relation between observed and predicted values were visualized for actual water repellency only, because we found it to be more significant with respect to field conditions in comparison to water repellency of air-dried samples.

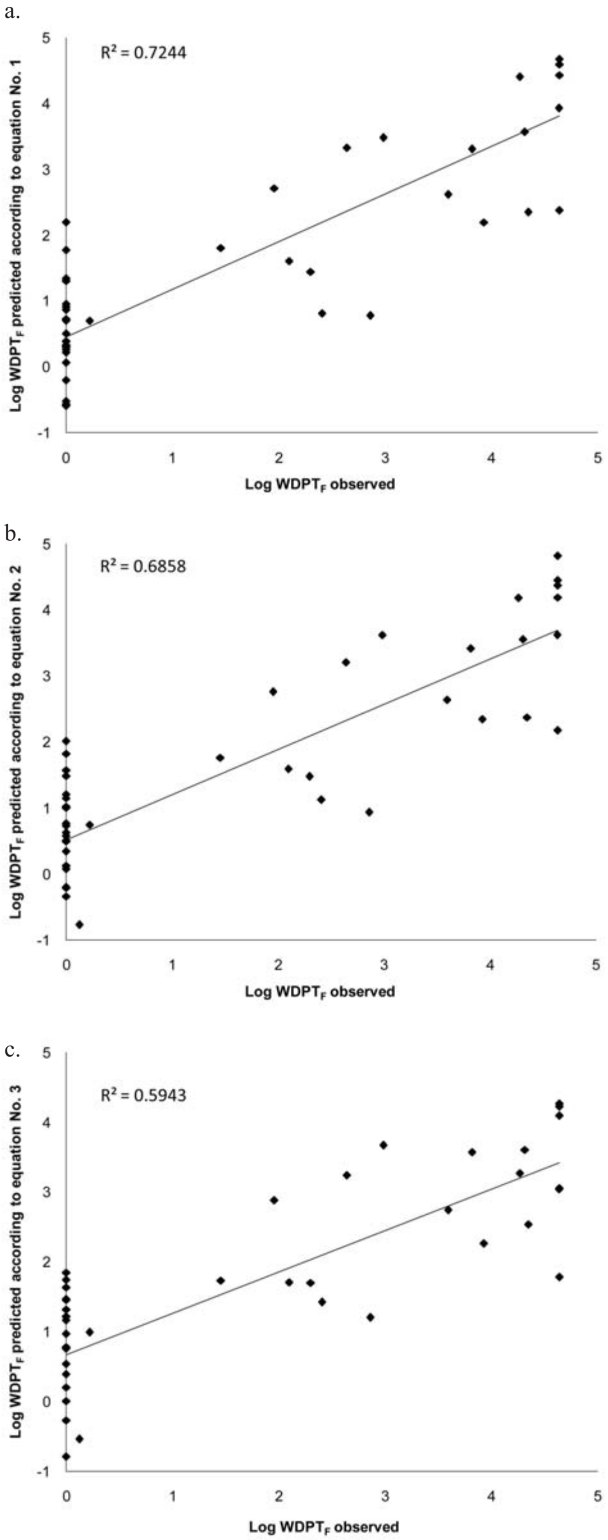

Fig. 4. The relation between observed soil water repellency values and those predicted according to three different regression equations presented in Table 5a.

Water Repellency and Soil Reaction

As already suggested, according to regression analysis performed on the whole population of 60 cases, the effect of soil reaction on soil wettability showed to be insignificant because of higher pH values of fire-affected soils. At the same time these exhibited relative high degrees of water repellency (Table 3). By comprising of the samples affected by fire into statistical population together with soils, which are from point of fire impact considered as reference, assessment of the relation between pH and water repellency becomes complicated. Moreover, by mixing fire-affected soils together with reference, we are ignoring the possible difference in quality of soil organics caused by combustion during fire. Such a change is in turn capable of affecting water repellency. Therefore the multiple regression analysis was performed also on 45 cases without fire-affected samples. Although reducing the number of observations in any statistical processing is accompanied by lower significance of subsequent conclusions, we found a considerably higher coefficient of multiple determination in regression analysis with fire-affected samples excluded. Thus, besides field moisture and content of organic carbon it was found that soil pH value is partially controlling susceptibility of soil to exhibit water repellence as well, considering fire-unaffected soil material. Whereas organic carbon content as stand alone variable expresses mainly quantitative aspects of SOM composition, pH value in certain cases characterizes quality of soil organics as well. It reflects dissociation status of organic functional (e.g. carboxylic) groups. According to Horne and McIntosh [32] the hydrophobicity of carboxylic functional groups increases with the decreasing degree of their dissociation. Although this concept is corresponding with results of multiple regression analysis presented here, we suggest that in forest soils, particularly in a relatively cold and humid environment, such as the High Tatras Mts., lower soil reaction values are related to high content of accumulated organic matter. The formation of acidic (mor) humus in these soils proceeds, because particular organic substances originating from vegetation (e.g. conifers, mosses, heath plants) and/or microbial biomass are being accumulated in soil surface in sufficient amounts due to relative cold and humid climatic conditions. If for some reason water content falls below a certain level, probability of water repellency development increases.

Conclusions

Our study has confirmed that soil surface horizon, even in a relatively moist and cold climate, might exhibit significant degrees of water repellency, especially during drier summer weather periods. A remarkable portion of samples exhibited water repellency in their field water content, and also after laboratory drying to constant weight. The high degree of soil water repellency for the majority of samples taken from reference site suggest that this phenomenon is partaking on soil character in the area regardless of katabatic wind impact on forest canopy. However, the effect of windblown and successive events resulted in change of conditions of former forest floor, and hence affected spatial variability of certain topsoil properties. From measured characteristics of topsoil water repellency and water content are properties in case of which observed differences between four groups of samples taken at individual experimental sites are, besides other factors, related to windblown-induced changes and subsequent management practices. The only site at which water repellency in field conditions was not detected is T3. Topsoil samples taken from this site were from point of wettability significantly different from other investigated topsoils, which might be associated with high levels of field soil moisture of concerned samples. Since topsoil at the T3 site did not exhibit water repellency in conditions during the driest summer period, it is expected that it would also cease during the rest of the year. Lasting of such moist conditions in topsoil in the area might be favourable for particular orientation of amphiphilic (amphipathic) substances. Hydrophilic functional groups or parts of the molecules are pointing outwards, and as a result soil is wetted more readily. It is probable that this particular way of arrangement is not changed also when soil is subjected to drying at relatively low temperatures (e.g. 20-24°C), which might suggest that possibly any amount of energy is needed to change such orientation and induce water repellency.

It was found that a certain portion of spatial variability observed in set of WDPT and MED values is possible to explain by means of regression analysis. The results suggest that in the case of forest soils studied here it is more appropriate to apply multiple regressions in comparison to simple for any predictions of repellency. Simple regression analysis provided much more limited explanation of WDPT and MED variances in comparison to multiple ones. According to obtained regression models the explained portion of variability detected in water repellency testing is caused by variability in field water and organic carbon content, with soil moisture being of greater predictive importance from the two considered variables. However, in regression analysis increased values of soil reaction of fire affected water repellent samples lowered predicting significance of pH. Considering the conditions of fire-unaffected topsoil material, it was found that besides field water and organic matter contents, susceptibility of soil to become water repellent is significantly controlled also by soil reaction.

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