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PLANTS AND BIOLOGICAL SOIL CRUST INFLUENCE THE HYDROPHYSICAL PARAMETERS AND WATER FLOW IN AN AEOLIAN SANDY SOIL

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This study tested the hypothesis that the changes in hydrophysical parameters and heterogeneity of water flow in an aeolian sandy soil have the same trend as the process of succession. Three sub-sites were demarcated at the area of about 50 m x 50 m. The first sub-site was located at the pine-forest glade covered with a biological soil crust and represented the initial stage of succession. The second sub-site was located at the grassland and represented more advanced stage of succession. The third sub-site was located at the pine forest with 30-year old Scots pines and represented advanced stage (close to climax) of succession. The sandy soil at the surface was compared to the soil at the pine-forest glade at 50 cm depth, which served as a control because it had a similar texture but limited impact of vegetation or organic matter. It was found that any type of vegetation cover studied had a strong influence on hydrophysical parameters and heterogeneity of water flow in an aeolian sandy soil during hot and dry spells. The changes in some hydrophysical parameters (WDPT, *R*, *k*(–2 cm), S_w(–2 cm), ECS and DPF) and heterogeneity of water flow in an aeolian sandy soil had the same trend as the process of succession, but it was not so in the case of K_s and S_e(–2 cm), probably due to the higher content of smaller soil particles in grassland soil in comparison with that content at other sub-sites. Both the persistence and index of water repellency of pure sand differed significantly from those of grassland, glade and forest soils. The highest repellency parameter values in forest soil resulted in the lowest value of both the water sorptivity and hydraulic conductivity in this soil in comparison with other soils studied. The highest value of ethanol sorptivity and the lowest value of saturated hydraulic conductivity in the grassland soil in comparison with other soils studied were due to the higher content of fine-grained (silt and clay) particles in the grassland soil. The effective cross section and the degree of preferential flow of pure sand differed significantly from those of grassland, glade and forest soils. The change in soil hydrophysical parameters due to soil water repellency resulted in preferential flow in the grassland, glade and forest soils, while the wetting front in pure sand area exhibited a form typical of that for stable flow. The latter shape of the wetting front can be expected in the studied soils in spring, when soil water repellency is alleviated substantially. The columnar shape of the wetting front, which can be met during heavy rains following long dry and hot spells, was attributed to redistribution of applied water on the surface to a series of micro-catchments, which acted as runon and runoff zones.

KEY WORDS: Sandy Soil, Vegetation, Water Repellency, Hydrophysical Parameters, Water Flow.

ABBREVIATIONS**:** BSC – biological soil crust, DPF – degree of preferential flow, ECS – effective cross section, WDPT – water drop penetration time.

Ľubomír Lichner, Ladislav Holko, Natália Žuková, Karsten Schacht, Kálmán Rajkai, Nándor Fodor, Renáta Sándor: VPLYV RASTLÍN A BIOLOGICKÉHO PÔDNEHO POKRYVU NA HYDROFYZIKÁLNE PARAMETRE A PRÚDENIE VODY V PIESOČNATEJ PÔDE. J. Hydrol. Hydromech., *60*, 2012, 4; 51 lit., 4 obr., 2 tab.

V príspevku sa testovala hypotéza, že zmeny hydrofyzikálnych parametrov a heterogenita prúdenia vody v piesočnatej pôde majú rovnaký trend ako proces sukcesie. Na ploche asi 50 m x 50 m sa vytýčili tri parcely. Prvá parcela sa nachádzala na čistine pokrytej biologickým pôdnym pokryvom a reprezentovala počiatočné štádium sukcesie. Druhá parcela sa nachádzala na zatrávnenej ploche a reprezentovala rozvinutejšie štádium sukcesie. Tretia parcela sa nachádzala v borovicovom lese a reprezentovala rozvinuté štádium sukcesie (blízke ku klimaxovej vegetácii). Piesočnatá pôda na povrchu parciel sa porovnávala s pôdou z čistiny v hĺbke 50 cm, ktorá slúžila ako kontrola, pretože mala skoro rovnakú textúru, avšak veľmi malý vplyv vegetácie alebo organickej hmoty. Zistili sme, že akýkoľvek typ študovaného vegetačného pokryvu mal veľký vplyv na hydrofyzikálne parametre a heterogenitu prúdenia vody v piesočnatej pôde počas horúcich a suchých období. Zmeny niektorých hydrofyzikálnych parametrov (WDPT, R, k(–2 cm), S_w(–2 cm), ECS a DPF) a heterogenity prúdenia vody v piesočnatej pôde mali rovnaký trend ako proces sukcesie, neplatilo to však v prípade K_s a S_e(–2 cm), pravdepodobne v dôsledku vyššieho obsahu malých pôdnych častíc v pôde s trávnatým pokryvom v porovnaní s inými parcelami. Stálosť aj index vodoodpudivosti čistého piesku sa štatisticky významne líšili od hodnôt týchto parametrov v pôde pod trávou, biologickým pôdnym pokryvom a borovicami. Najvyššie hodnoty parametrov vodoodpudivosti v tráve pod borovicami mali za následok najnižšie hodnoty sorptivity pre vodu a hydraulickej vodivosti v tejto pôde v porovnaní s ostatnými študovanými pôdami. Najvyššie hodnoty sorptivity pre etanol a najnižšie hodnoty nasýtenej hydraulickej vodivosti v pôde pod trávou v porovnaní s inými pôdami boli pravdepodobne spôsobené vyšším obsahom malých pôdnych častíc v tejto pôde. Efektívny prierez (ECS) a stupeň preferovaného prúdenia (DPF) čistého piesku sa štatisticky významne líšili od hodnôt týchto parametrov v pôde pod trávou, biologickým pôdnym pokryvom a borovicami. Zmeny hydrofyzikálnych parametrov pôdy v dôsledku jej vodoodpudivosti mala za následok preferované prúdenie v pôde pod trávou, biologickým pôdnym pokryvom a borovicami, zatiaľ čo čelo omáčania v čistom piesku malo tvar typický pre stabilné prúdenie. Takýto tvar čela omáčania možno vo všetkých študovaných pôdach očakávať na jar, keď je vodoodpudivosť pôdy podstatne znížená v dôsledku jej zvýšenej vlhkosti. Čelo omáčania v tvare prstov, ktoré možno očakávať počas prívalových dažďov nasledujúcich po dlhých suchých a horúcich obdobiach, možno pričítať redistribúcii vody na povrchu pôdy do viacerých mikropovodí, ktoré sa správali ako vtokové a odtokové oblasti.

KĽÚČOVÉ SLOVÁ: piesočnatá pôda, vegetácia, vodoodpudivosť, hydrofyzikálne parametre, prúdenie vody.

Introduction

Plants and biological soil crust (= a living groundcover, resulting from an intimate association between soil particles and cyanobacteria, algae, microfungi, lichens, mosses and liverworts) can influence the hydrophysical parameters and water flow in soils considerably, mainly due to soil water repellency (e.g., *Dekker* and *Ritsema*, 1994; *Buczko* et al., 2006; *Wessolek* et al., 2009; *Wine* et al., 2012). Very large infiltration rates (up to 300 mm h^{-1}), found in sandy vegetation-less areas (*Yair*, 2003), can decrease significantly if biological soil crust (BSC), grasses, herbs or coniferous trees are present. Decreased infiltration rates can be caused by the clogging of soil pores by microbially produced polysaccharides, the inherent water-repellent properties of some crusts, and surface-sealing processes (*Doerr* et al., 2000). Sealing is caused by the combined swelling of microorganisms (e.g. cyanobacterial filaments and gelatinous lichens have the capacity to absorb ten times or more their volume in water) and soil fine particles when wetted (*Belnap* and *Lange*, 2003). Moreover, coniferous trees produce waxes and resins that are hydrophobic, in addition to supporting microbial communities dominated by fungi (*Nash*, 2008).

Soil water repellency, caused by organic compounds derived from living or decomposing plants or microorganisms (*Doerr* et al., 2000; *Hallett*, 2007; *Goebel* et al., 2011), is a transient soil property, which tends to be both spatially and temporally highly variable. It often disappears after periods of prolonged soil wetting, but will usually reemerge during drier periods when soil moisture falls below a critical threshold (*Dekker* et al., 2001). Reestablishment of water repellency may be associated with the energy input during heating or a new input of hydrophobic substances (*Doerr* and *Thomas*, 2000).Water repellency can be alleviated by wetting agents (*Aamlid* et al., 2009; *Moore* et al., 2010) and addition of kaolinite clays (*Lichner* et al., 2006). It was found that slight reductions in soil water content could cause substantial reductions in soil wettability (*Czachor* et al., 2010). As a result, heavy rains following long dry and hot spells can lead to surface runoff, soil erosion and worsening water quality (*Pekárová* et al., 2009; *Onderka* et al., 2012; *Pavelková* et al., 2012). Some other consequences of soil water repellency are reduction in wetting rates of dry soils and plant available water, induction of preferential flow resulting in irregular moisture patterns, patchy growth of plants, and increase in solute transport through destined flow channels or fingers (*Wessolek* et al., 2008). Dye tracer technique is convenient to distinguish a different nature of preferential flow from the staining patterns within the vertical and horizontal field scale sections (*Lipsius* and *Mooney*, 2006; *Mooney* and *Morris*, 2008; *Kodešová* et al., 2012). Transport of microorganisms in sand or sandy soil can be simulated using HYDRUS-1D (*Kodešová* et al., 2011).

Actual water repellency of dune/aeolian sand, defined as water repellency of field-moist sand (*Dekker* and *Ritsema*, 1994), is not restricted to the dune surface, but it can be detected in deeper depths (up to 60 cm, as presented in *Dekker* et al., 2000). Both the water flow paths and intermediate dry soil persist over time during summer, but over annual cycles their spatial arrangements can change completely (*Wessolek* et al., 2009).

The objective of this study was to quantify the influence of vegetation on hydrophysical parameters and heterogeneity of water flow in a sandy soil emerging during a simulated heavy rain following a long hot and dry period. We expected that the changes in hydrophysical parameters and heterogeneity of water flow have the same trend as the process of succession.

Material and methods

Study site

The study site called "Mláky II"(48°37'10'' N, 16°59'50'' E) is located at Sekule village in the Borská nížina lowland of southwest Slovakia (Fig. 1). Its area is about 1000 km^2 and 41% of it is covered by aeolian sand dunes. The region is in a transition zone between temperate oceanic and continental climates. The mean annual temperature is 9°C. The mean annual precipitation is 550 mm and it is mainly summer-dominant. The climate in summer tends to consist of long hot and dry spells interspersed with intense rainfalls, as a result of climate change (*Faško* et al., 2008).

Three sub-sites, situated at the area of about 50 m x 50 m, formed the basis of our study. The first sub-site was located at the pine-forest glade covered with BSC and represented the initial stage of succession (Fig. 2a). The second sub-site was located at the synanthropized grassland dominated by grasses (*Calamagrostis epigejos*, *Agrostis tenuis*), and represented more advanced stage of succession (Fig. 2b). The third sub-site was located at the pine forest with 30-year old Scots pines (*Pinus sylvestris*), and represented advanced stage of succession (Fig. 2c). Climax is represented by oak-pine forests here, which are replaced by pine monocultures nowadays. The sandy soil at the surface was compared to soil sampled at the pine-forest glade at 50 cm depth, which served as a control because it had a similar texture but limited impact of vegetation or organic matter. The soil at the glade sub-site supported a sparse cover of mosses (*Dicranum polysetum*, *Ditrichum heteromallum, Hypnum cupressiforme, Polytrichastrum fumosum*, *Polytrichum piliferum*) and lichens (*Cladonia* sp.), and occasionally, grasses (*Corynephorus canescens*) (*Šomšák* et al., 2004). Some areas in the glade had exposed bare soil, where the components of BSC are present, but invisible. The soil microscopic fungi *Alternaria alternata*, *Aspergillus fisheri*, *A. glaucus*, *A. niger*, *Aureobasidium pullulans*, *Chaetomium globosum*, *Humicola fuscoatra*, *Mortierella* sp., *Mycelia sterilia*, *Paecilomyces* sp., *Penicillium aspergilloides*, *P. janthinellum*, *P. decumbens*, and *Trichoderma koningii* (*Lichner* et al., 2007), cyanobacteria *Leptolyngbya* sp., and algae *Bracteacoccus* sp., *Choricystis minor*, *Eustigmatos* cf. *polyphem*, *Interfilum* sp., *Klebsormidium* sp. div., *Mychonastes zofingiensis*, *Stichococcus bacillaris*, *Tribonema minus*, *Zygogonium ericetorum* (*Lichner* et al., 2012) have been recorded at the studied site. The above-mentioned components of BSC are present at all the three sub-sites, but the dominant impact on soil hydrophysical properties have grass and herbs at the grassland sub-site and pines at the forest sub-site. Soil of the experimental sub-sites is formed by aeolian sand, and it is classified as a Regosol (*WRB*, 2006) and has a sandy texture (*Soil Survey Division Staff*, 1993). The mineralogy of the aeolian sand was primarily siliceous sand (silica content up to 90%), with a low content of primary minerals (spars and micas) (*Kalivodová* et al., 2002). Physical and chemical properties of the soil samples are presented in Tab. 1.

Field methods

The persistence of water repellency was measured by means of the water drop penetration time (WDPT) test. The WDPT test measures how long the hydrophobicity persists on a porous surface. It relates to the hydrological implications of hydrophobicity because the amount of surface runoff is affected by the time required for the infiltration of droplets (*Doerr*, 1998). In this study, 58 ± 5 μL drops of distilled water from a medicinal dropper were placed onto the soil surface and the time required for infiltration was recorded. A standard droplet release height of approximately 10 mm above the soil surface was used to minimise the cratering effect on the soil surface.

Fig. 1. Location of the study site "Mláky II"; the black areas represent location of aeolian sand dunes in the Borská nížina lowland (adapted after *Kalivodová* et al., 2002).

Field measurements of the cumulative infiltration *vs.* time relationships were performed using a minidisk infiltrometer (4.5 cm in diameter) under a negative tension h_0 = –2 cm. Prior to the measurements, the litter layer was removed gently to prevent disturbance of the mineral soil.

The sorptivity $S(h_0)$ was estimated from the first term of the Philip infiltration equation (*Philip*, 1957):

$$S(h_0) = I / t^{1/2}. \quad (1)$$

Eq. (1) was used to calculate the sorptivity of both water, S_w(–2 cm), and ethanol, S_e(–2 cm), from the cumulative infiltration vs. time relationships taken with the minidisk infiltrometer during early-time (<180 s) infiltration of water and ethanol, respectively.

Zhang (1997) proposed to use the first two terms of the Philip infiltration equation to fit the cumulative infiltration vs. time relationship and estimate the hydraulic conductivity $k(h_0)$:

$$k(h_0) = C_2/A, \quad (2)$$

where A is a dimensionless coefficient. Eq. (2) was used to estimate the hydraulic conductivity k(–2 cm) in this study, using A = 1.8 for sandy soil and suction h_0 = –2 cm from the Minidisk Infiltrometer User's Manual (*Decagon*, 2007).

a)

b)

c)

Fig. 2. Photographs of (a) pine-forest glade surface covered by a biological soil crust with sparse tussocks of grass *Corynephorus canescens*, (b) grassland surface dominated by grasses (*Calamagrostis epigejos*, *Agrostis tenuis*), and (c) forest subsite with 30-year old Scots pines (*Pinus sylvestris*). (Colour version of the figure can be found in the web version of this article.)

T a b l e 1. Physical and chemical properties of the studied soils from site Mláky II taken under different vegetation cover.

Sub-site	Depth [cm]	Sand [%]	Silt [%]	Clay [%]	$CaCO_3$ [%]	C [%]	pH(H_2O)	pH(KCl)
Pure sand	50–55	94.9	1.7	3.4	<0.05	0.03	5.54	4.20
Grassland	0–5	91.3	2.8	5.9	<0.05	0.99	5.14	3.91
Glade	0–5	94.2	0.8	5.0	<0.05	0.11	5.52	3.96
Pine forest	0–1	95.1	2.3	2.6	<0.05	0.83	5.65	4.39

The index of water repellency R was calculated from (*Hallett* et al., 2001):

$$R = 1.95\, S_e(-2\text{ cm}) / S_w(-2\text{ cm}). \quad (3)$$

Infiltration measurements in the field under a small positive pressure head h_0 = 4 cm were also performed repeatedly at all the sub-sites using a double-ring infiltrometer with an inner-ring diameter of 24.5 cm, buffer ring diameter of 34.5 cm, and height of 23.5 cm. Fitting the cumulative infiltration vs. time relationship with the two-term Philip infiltration equation:

$$I \approx St^{1/2} + m\, K_s\, t \quad (4)$$

with m = 0.667 being the most frequently used value (*Kutílek* and *Nielsen*, 1994), was used to estimate the saturated hydraulic conductivity K_s in this study.

The dye tracer experiments were carried out at three 100 cm x 100 cm plots (demarcated at the forest, glade, and grassland sub-sites) and one 50 cm x 100 cm plot (demarcated in pure sand sub-site) in the way similar to that described by *Bachmair* et al. (2009) and *Kramers* et al. (2009). The tracer (Brilliant Blue FCF with a concentration 10 g L^{-1}) was used to observe the pattern of water flow in the soil. A water amount of 100 mm was applied by a sprinkler consisting of a board supporting 1600 needles with a diameter of 0.5 mm (*Homolák* et al., 2010) at the forest and glade sub-sites. An amount of 50 mm water was applied manually with a watering can at the pure sand sub-site and 20 mm and 70 mm water at two smaller subplots (50 cm x 100 cm) of the grassland plot. Thirty minutes after sprinkling, vertical sections were excavated 10 cm apart and their clean soil profiles photographed with a digital camera. The photographs have been digitally corrected and georeferenced using standard GIS software. Detailed information of the plots, meteorological data and dye tracer techniques were published by *Homolák* et al. (2009) and *Lichner* et al. (2011). The amounts and intensities of water applied were choosen to be big enough for subsurface flow and aquifer recharge as short thunderstorms (10 min) or low intensity rains contribute to water resources at the plant level (transpiration) only (*Cammeraat* et al., 2010).

To assess the results of dye tracer experiments, the ECS approach presented in *Täumer* et al. (2006) was modified (*Lichner* et al., 2011). The fraction of total water content change was determined from the stained area. The picture of each vertical section was divided into 10 vertical bands with a width of 10 cm, and the numbers n_j of stained 5 cm x 5 cm pixels were calculated in each band j. It was supposed that the water content change in the band is proportional to the number of stained pixels. The number of stained pixels is not an integer if the whole area of pixels is not stained. The fraction of total water content change f_j (the ratio between the water content change in band j and the total water content change in the vertical profile) for each band was calculated using

$$f_j = n_j \Big/ \sum_{j=1}^{10} n_j \quad \text{with} \quad \sum_{j=1}^{10} f_j = 1. \quad (5)$$

The fractions f_j were ranked in descending order and presented against the fraction of cross-sectional area (11 dots in Fig. 3b). A beta distribution

$$p(x;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{(\alpha-1)}(1-x)^{\beta-1}$$

$$(\alpha > 0,\ \beta > 0,\ 0 \le x \le 1) \quad (6)$$

(where Γ is the Gamma function (or Euler's integral of the second kind) and α and β are the parameters) was fitted to the data and the Levenberg-Marquardt algorithm was used to optimize the parameters α and β. According to the definition in *Täumer* et al. (2006), the effective cross section, ECS was then estimated as the fraction of the total area that corresponds to the 90% of water content change in vertical section (Fig. 3b). ECS equals to 0.9 for piston flow, and it decreases with an increase in the impact of preferential flow in the soil.

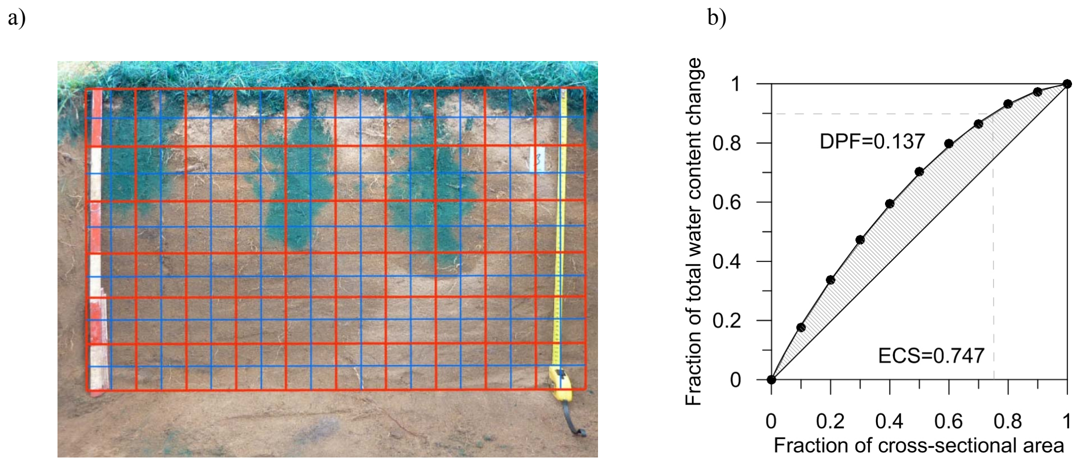

Fig. 3. Estimation of effective cross section (ECS) and degree of preferential flow (DPF) from the image of a vertical section of dyed soil, taken in the grassland soil at the distance of 30 cm from the front edge during the 2010 tracer experiment; (a) The image of the vertical section with 10 cm (red lines) and 5 cm (blue lines) grids used for an estimation of the fractions of total water content change against the fractions of total cross-sectional area; (b) The plot of the cumulative water content changes against the cumulative cross-sectional area (black dots), with ECS estimated as the fraction of the total cross-sectional area that corresponds to the 90% of total water content change, and DPF presented as the shaded area between beta-function fitted to the data and straight line representing the piston flow. (Colour version of the figure can be found in the web version of this article.)

The degree of preferential flow, DPF, equal to the area between the beta distribution curve and the 1:1 line (the line represents the distribution of fraction of total water content change vs. fraction of cross-sectional area for a piston flow), was also used to quantify the heterogeneity of water flow in soil (Fig. 3b). The DPF was calculated from

$$DPF = \int_{x=0}^{1} p(x;\alpha,\beta)\mathrm{d}x - 0.5. \qquad (7)$$

DPF increases with an increase of the impact of preferential flow in the soil from 0 for piston flow to almost 0.5 for the case when all the flow in the soil is realized through a narrow preferential path (e.g., a crack in heavy clay soil).

The differences in all the parameters measured and calculated for the pure sand, glade, forest and grassland plots were tested using the one-way Anova statistics. The normal distribution and homogeneity in variance was assumed and the significance of the differences was tested at P = 0.05. If the above assumptions were not fulfilled, the alternative non-parametric one-way analysis (the Kruskal–Wallis method) was used to test the statistical significance of the differences among the sub-sites.

Results and discussion

The hydrophysical parameters of the sub-sites with different vegetation cover are presented in Tab. 2. The mean values of WDPT in the grassland, glade, and forest soils were about 350-, 950-, and 1600-times higher than that of the pure sand, respectively, and they revealed statistically significant differences between the pure sand and sandy soil under the mentioned vegetation. The mean values of the index of water repellency in the grassland, glade, and forest soils were 10-, 34-, and 123-times higher than that of the pure sand, respectively, and they revealed statistically significant differences between the pure sand and sandy soil under mentioned vegetation. It can be seen that the hydrophobic waxes from pine needles can be the cause of more severe repellency than the thatch (the layer of organic matter between the mineral soil and the green grass) and mucilages of grasses or mucilages of BSC.

The mean values of water sorptivity in the grassland, glade, and forest soils were 7%, 10%, and 2% of that of the pure sand, respectively. These values for grassland and glade soils differed significantly from both that of pure sand and that of forest soil. The mean values of hydraulic conductivity in the grassland, glade, and forest soils were 5%, 7%, and 1% of that of the pure sand, respectively. These values for grassland and glade soils differed significantly from those of the pure sand and forest soil. It means that the highest value of both the persistence

(WDPT) and index of water repellency in the forest soil resulted in the lowest value of water sorptivity and hydraulic conductivity. The statistical relationships between either the water sorptivity, hydraulic conductivity or saturated hydraulic conductivity versus either WDPT or water repellency index were presented in *Lichner* et al. (2010).

T a b l e 2. Mean value (MV) and standard error (SE) of the water drop penetration time (WDPT), water repellency index R, sorptivity S_w (–2 cm) for water and S_e (–2 cm) for ethanol, hydraulic conductivity k (–2 cm) and saturated hydraulic conductivity K_s, effective cross section (ECS), and degree of preferential flow (DPF) of the studied soils from site Mláky II taken under different vegetation cover.

Attribute	Sub-site							
	Pure sand		Glade		Grassland		Pine forest	
	MV	SE	MV	SE	MV	SE	MV	SE
WDPT [s]	1 ^{a}	0	958 ^{b}	705	347 ^{b}	103	1601 ^{b}	547
R [–]	0.816 ^{a}	0.166	27.9 ^{b}	15.1	8.42 ^{b}	2.74	100.5 ^{b}	36.9
S_w [–2 cm] [mm s$^{-1/2}$]	7.60 ^{a}	0.982	0.788 ^{b}	0.282	0.530 ^{b}	0.130	0.185 ^{c}	0.0623
S_e [–2 cm] [mm s$^{-1/2}$]	2.67 ^{a}	0.292	3.53 ^{a}	0.680	1.15 ^{b}	0.824	2.26 ^{a}	0.425
k [–2 cm] [mm s^{-1}]	0.478 ^{a}	0.0723	0.0314 ^{b}	0.0122	0.0258 ^{b}	0.0100	0.00460 ^{c}	0.00197
K_s [mm s^{-1}]	0.523 ^{a}	0.0484	0.162 ^{b}	0.0127	0.0856 ^{c}	0.00706	0.134 ^{b}	0.0204
ECS [m^{2} m^{-2}]	0.869 ^{a}	0.00780	0.819 ^{b}	0.0200	0.795 ^{b}	0.0204	0.805 ^{b}	0.0183
DPF [–]	0.0364 ^{a}	0.00592	0.0701 ^{b}	0.0142	0.0996 ^{b}	0.0151	0.0777 ^{b}	0.0124

Different superscript letters within a row indicate a significant difference at $P < 0.05$

The sandy soil in our study site had a very low percentage of fine material (3–6% clay; Tab. 1), making it structurally poor in the surface horizon where the macroporosity status is also likely low. Low levels of poorly aggregated silts and clays could also block the matrix pores, restricting water flow (*Eldridge* et al., 2002). *Morris* et al. (2008) found that Brilliant Blue FCF is sorbed mainly by the clay fraction of soils, however, the low percentage of clay was enough for staining the preferential paths in studied soils.

The mean values of ethanol sorptivity in the grassland, glade, and forest soils were 43%, 132%, and 85% of that of the pure sand, respectively. This value for grassland soil differed significantly from those of forest and glade soils, as well as pure sand. The lowest value of ethanol sorptivity in the grassland soil in comparison with other studied soils was probably due to the higher content of fine-grained (silt and clay) particles in the grassland soil (cf. Tab. 1).

The mean values of saturated hydraulic conductivity in the grassland, glade, and forest soils were 16%, 31%, and 25% of that of the pure sand, respectively. These values for forest and glade soils differed significantly from those of pure sand and grassland soil. The lowest value of saturated hydraulic conductivity in the grassland soil in comparison with glade and forest soils was probably due to the higher content of fine-grained (silt and clay) particles in the grassland soil (cf. Tab. 1). This is consistent with findings of *Ravi* et al. (2007) that silt and clay content in sand dunes is negatively correlated with infiltration rates.

The mean values of the effective cross section in the grassland, glade, and forest soils were 91%, 94%, and 93% of that of the pure sand, respectively, and they revealed statistically significant differences between the pure sand and sandy soil under vegetation.

The mean values of the degree of preferential flow in the grassland, glade, and forest soils were 2.7-, 1.9-, and 2.1-times higher than that of the pure sand, respectively, and they revealed statistically significant differences between the pure sand and sandy soil under the mentioned vegetation.

During dye tracer experiments at grassland, glade and forest sub-sites, we observed that surface water pooled into small micro-depressions. The shape of the wetting front in vertical section exposed e.g. at the grassland sub-site at a distance of 30 cm from the leading edge and after 20 mm of infiltration (Fig. 3a) was similar to that of the unstable fingered flow with air-confined condition (*Wang* et al., 2000). Based on the ponded area observed during water application, we attribute the columnar shape (*Morales* et al., 2010) of the wetting front to redistribution of applied water on the surface to a series of micro-catchments, which acted as runon and runoff zones. The columns rarely showed concentric horizontal sections, most of the forms were irregular. The plot of the cumulative water content changes against the cumulative cross-sectional area (black dots), ECS and DPF for the above-mentioned vertical section are presented in Fig. 3b). You can compare this figure with Fig. 4 in

Lichner et al. (2011), taken in grassland soil at the distance of 60 cm from the front edge during the same tracer experiment, and see the impact of different amount of applied water (20 mm in this figure and 70 mm in that published in *Lichner* et al., 2011) on the shape of wetting front. Nevertheless, the ECS and DPF values were not influenced by the amount of applied water, and therefore, they both were evaluated statistically (mean values and standard errors in Tab. 2) as one set.

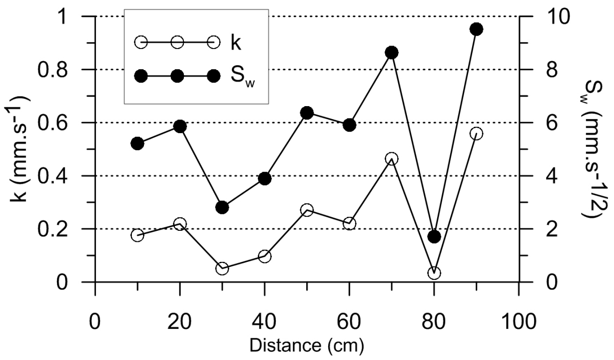

Fig. 4. Measurements of k(–2 cm) and S_w(–2 cm), taken in a 100-cm transect demarcated in the pure sand area.

On the other hand, the wetting front in pure sand area exhibited a form typical of that for stable flow with "air-draining" condition, when the soil air is allowed free to drain from ahead of the wetting front through an air exit at the bottom (*Wang* et al., 2000). A lack of preferential flow is confirmed by the magnitude of the effective cross section which ranged from 0.839 to 0.882, and the degree of preferential flow which ranged from 0.0249 to 0.0574 (*Lichner* et al., 2011). This shape of the wetting front (cf. Fig. 2a) in *Lichner* et al., 2011) can be expected in vegetation covered sub-sites in spring, when soil water repellency is alleviated substantially.

Variability in hydrophysical parameters could result partly from inherent properties of aeolian sands not influenced by plant/crust cover. Measurements of S_w(–2 cm) and k(–2 cm) taken in a 100-cm transect demarcated in the pure sand area (Fig. 4) revealed that the water sorptivity and hydraulic conductivity, taken in 10-cm distance, can change with about an order of magnitude (S_w(–2 cm) changed from 1.72 mm s$^{-1/2}$ in 80 cm to 9.52 mm s$^{-1/2}$ in 90 cm, and k(–2 cm) changed from 33.9 μm s^{-1} in 80 cm to 559 μm s^{-1} in 90 cm). This variability can be increased even more by vegetation cover, as it was presented for centimetre scale in *Orfánus* et al. (2008).

Testing the statistical significance of the differences among the sub-sites showed three types of changes in hydrophysical parameters and heterogeneity of water flow in an aeolian sandy soil in comparison to the process of succession. The mean values of the persistence (WDPT) and index (R) of soil water repellency, effective cross section ECS, and the degree of preferential flow DPF changed in the order: Pure sand < Glade soil ≈ Grassland soil ≈ Forest soil, as the differences between glade, grassland and forest soils were not statistically significant. The mean values of water sorptivity S_w(–2 cm) and hydraulic conductivity k(–2 cm) changed in the order: Pure sand > Glade soil ≈ Grassland soil > Forest soil, as the differences between glade and grassland soils were not statistically significant. The mean values of ethanol sorptivity S_e(–2 cm) changed in the order: Pure sand ≈ Glade soil ≈ Forest soil > Grassland soil, and their trend was different from the process of succession. The mean values of saturated hydraulic conductivity K_s changed in the order: Pure sand > Glade soil ≈ Forest soil > Grassland soil, and their trend was different from the process of succession, too. The lowest values of both S_e(–2 cm) and K_s in the grassland soil in comparison with other studied soils were probably due to the higher content of fine-grained (silt and clay) particles in the grassland soil (cf. Tab. 1).

Conclusions

It was found that any type of vegetation cover studied had a strong influence on hydrophysical parameters and heterogeneity of water flow in an aeolian sandy soil during hot and dry spells. The changes in some hydrophysical parameters (WDPT, R, k(–2 cm), S_w(–2 cm), ECS and DPF) and heterogeneity of water flow in an aeolian sandy soil had the same trend as the process of succession, but it was not so in the case of K_s and S_e(–2 cm), probably due to the higher content of smaller soil particles in grassland soil in comparison with that content at other sub-sites. The change in soil hydrophysical parameters due to soil water repellency resulted in preferential flow in the grassland, glade and forest soils, while the wetting front in pure sand area exhibited a form typical of that for stable flow. The latter shape of the wetting front can be expected in the studied soils in spring, when soil water repellency is alleviated substantially. The columnar shape of the wetting front, which can be met during heavy rains following long dry and hot spells, was attributed to redistribution of applied water on the surface to a series of micro-catchments, which acted as runon and runoff zones.

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