ORIGINAL ARTICLE

Differences in moisture pattern, hydrophysical and water repellency parameters of sandy soil under native and synanthropic vegetation

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Abstract

The main goal of the study was to estimate the differences in moisture pattern, hydrophysical and soil water repellency (SWR) parameters of sandy soil profiles at two grassland sites, separated by a distance of about 100 m, near Sekule village (southwest Slovakia). Site S1 was covered with natural vegetation formed by a process of primary succession on a sand dune, whilst site S2 was covered by a synanthropic vegetation, formed by spontaneous secondary succession. Soil sampling and infiltration experiments were performed at designated plots during June 2017 to determine hydrophysical and SWR parameters. Higher measured value of organic carbon content at site S2 resulted in the greater values of repellency index (RI) and lower values of hydraulic conductivity, $k(-2 \text{ cm})$, and sorptivity of water, $S_w(-2 \text{ cm})$ compared to S1. For evaluating the differences between estimated hydrophysical and SWR parameters of S1 and S2, a Welch's test of means (allowing for unequal group variances) was used, revealing significant differences in $S_w(-2 \text{ cm})$, and RI, at $p < 0.05$. Simultaneously designed infiltration experiments pointed out altered distribution in wetting pattern across the soil profile with different penetration depths: below 100 cm and 80 cm at S1 and S2, respectively. Although the observed moisture patterns showed different shapes and extensions, difference in the cumulative increase in soil water storage between 0 and 50 cm was not significant (35.1% and 36.8% of applied water) at S1 and S2, respectively. According to the results we can state that grasslands at sites S1 and S2 have different soil water repellency parameters and shape of moisture pattern, induced probably by finger flow. Nevertheless, the soil water retention capacity of site S2, formed by spontaneous secondary succession is nearly the same as the retention capacity of native grassland S1.

Keywords Grassland · Infiltration test · Moisture pattern · Sandy soil · Synanthropic and native vegetation

Introduction

Native vegetation refers to vegetation formed by primary succession, which is controlled by the climatic and environmental conditions and undisturbed by human activities. Primary succession is defined as vegetation development on newly formed or exposed substrate, characterized by low fertility (Gorham et al. 1979) in essentially lifeless areas in which the soil is incapable of sustaining life as a result of such factors as lava flows, newly formed sand dunes, or rocks left from a retreating glacier. A primary site does not contain biological legacy, neither previous vegetation and seed bank, nor organic matter derived from prior herbage. Succession of native vegetation takes place in an environment where external physio–chemical constraints are not undergoing major change: ecological succession leads naturally to increasing biological control of the environment and a stabilized ecosystem (Copper 1988). The vegetation sequence for dune succession tends to show a simple linear successional sequence of annuals, sand-binding dune grasses, cottonwoods, pines, and oak forest (Johnson and Miyanishi 2008). The compositional changes that characterize succession are the product of multiple factors, including disturbance characteristics, site history, dispersal limitation, abiotic stressors and biotic interactions that operate at a range of spatial scales (HilleRisLambers et al. 2012; Norden et al. 2015; Prach et al. 2016; del Moral and Titus 2018; Måren et al. 2018).

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So-called synanthropic vegetation occurs on the sites created or disturbed by man (Jarolímek et al. 1997). There is a progressive distribution of synanthropic species in Slovakia, which is influenced by mankind activities (Štrba and Gogoláková 2008). Synanthropic species are able to adapt to a variety of human activities gaining benefits from the artificial habitats that men create around them. Synanthropic vegetation is formed by process of secondary succession, defined as the replacement of pre-existing vegetation following a disturbance that disrupts the ecological preferences of the native species (Tallis et al. 1993).

Large-scale abandonment of low production croplands is typical in the last few decades in the eastern part of Europe; about 10–20% of croplands have been abandoned in Central and Eastern Europe (Hobbs and Cramer 2007). Abandoned croplands can act as excellent objects to study spontaneous secondary succession processes and to validate succession theories (see Rejmanek and van Katwyk 2005; Hegedüšová and Senko 2011; Li et al. 2016; Német et al. 2016). Analysis of spontaneous secondary succession as a grassland restoration practice has been studied on sandy old-fields in Hungary by Csecserits et al. (2011) and Albert et al. (2014). Successful spontaneous grassland recovery involves restoring biodiversity and all ecological functions (including water and nutrient regime) at the level of native grassland vegetation.

Grass cover can induce soil water repellency (SWR) in all soil types by both root exudates and thatch (the layer of organic matter between the mineral soil and green grass leaves). SWR can contribute to the development and propagation of unstable wetting fronts and preferential flow paths (Orfánus et al. 2014; Oostindie et al. 2017), enhanced overland flow, increased and accelerated aquifer contamination (Doerr et al. 2000), as well as reduced agricultural productivity and seed germination (Doerr et al. 2000).

The objectives of the present research were to estimate the differences in moisture (wetting) pattern, as well as hydrophysical and water repellency parameters of homogenous sandy soil under native and synanthropic grassland vegetation.

Material and methods

Study area

The experimental area is located at Mláky II near Sekule (48°37′10” N, 16°59′50″ E) in the Borská nížina lowland (southwest Slovakia). The altitude of study site is 150 m a. s. l. The climate is continental; mean annual temperature is 9 °C. Mean annual precipitation is 550 mm, and it is mainly summer-dominant (Klimatický atlas Slovenska 2015). Two study sites S1 and S2 (separated by the distance of about 100 m) were demarcated in this area. Aeolian sandy soil from

these sites is classified as an Arenosol (WRB 2006) and sandy texture was measured for whole soil profile (Soil Survey Division Staff 1993).

The phytosociological relevés were made according to the Zürich-Montpellier school using the 9-degree Braun-Blanquet scale of abundance and dominance on 27th June 2017 (Braun-Blanquet 1964). Plant nomenclature follows Marhold and Hindák (1998).

Site S1 represents an early stage of primary succession on sand dunes (Šurda et al. 2015; Lichner et al. 2018). Thickness of organic layer in the upper soil horizon is only 2 cm.

Its floristic composition shows the following phytocoenological relevé:

> Relevé 1. Borská nížina, Sekule – Mláky, 150 m, 48°37′10” N, 16°59′50″ E, 7367d, flat relief with sand, relevé area 5 × 5 m, E_1: 80%, E_0 15%, 27. 6. 2017, J. Kollár
> E_1: *Festuca rupicola* 3, *Carex supina* 1, *Festuca vaginata* 1, *Potentilla arenaria* 1, *Acetosella vulgaris* +, *Armeria maritima* +, *Eryngium campestre* +, *Tithymalus cyparissias* +, *Veronica dillenii* +, *Teucrium chamaedrys* r
> E_0: *Brachythecium albicans* 1, *Bryum capillare* 1, *Cladonia furcata* 1, *Hypnum cupressiforme* 1

Site S2 represents synanthropized vegetation formed by secondary succession. Site S2 was agriculturally used field, which was ploughed and fertilized. Abandonment of this site ca 20 years ago leads to spontaneous secondary succession. Thickness of organic layer of the upper soil horizon is 10 cm, which is a legacy of agricultural use. Site S2 is characterized by following phytocoenological relevé:

> Relevé 2. Borská nížina, Sekule – Mláky, close to the relevé 1, flat relief with sand, relevé area 5 × 5 m, E_1: 95%, E_0: 25%, 27. 6. 2017, J. Kollár
> E_1: *Poa angustifolia* 3, *Agrostis capillaris* 2a, *Cynodon dactylon* 2a, *Eryngium campestre* 2a, *Festuca rupicola* 2a, *Calamagrostis epigejos* 1, *Carex hirta* 1, *Convolvulus arvensis* 1, *Achillea millefolium* agg. +, *Hippochaete ramosissima* +, *Plantago lanceolata* +, *Tithymalus cyparissias* +, *Senecio jacobea* r
> E_0: *Brachythecium albicans* 3

Laboratory methods

Physical and chemical properties were determined in the ISI certified laboratories of the Soil Science and Conservation Research Institute, belonging to the Ministry of Agriculture of the Slovak Republic in Bratislava. They used the disturbed soil samples in amount 10 g/locality from the top soil (0–10 cm), taken from the experimental sites S1 (native

grassland species cover) and S2 (synanthropic grassland species cover) near Sekule, Slovakia. Soil organic carbon content, C_{org}, was determined by oxidation with $K_2Cr_2O_7$-H_2SO_4 and titration of non-reduced dichromate. Soil texture was determined by the pipette method (Gee and Bauder 1986; Sheldrick and Wang 1993). Soil pH was determined potentiometrically (1:2.5 – soil:distilled water). Percentage of calcium carbonate (% $CaCO_3$) was estimated by Calcimeter (Horváth et al. 2005).

Field methods

Soil sampling and also all described experiments were performed during June of 2017. Monthly mean air temperature for June 2017, measured at the adjacent meteo-station Kuchyňa was strongly above normal with deviation +2 °C compared with normal 1961–1990. Maximum monthly air temperature was 34.7 °C, monthly minimum 7.4 °C; monthly mean was 21.5 °C and precipitation total 55 mm. Measurements described below were taken after five consecutive days without precipitation.

Volumetric soil water content, θ, (m³ m⁻³) of the superficial (0–5 cm) soil layer was measured with the moisture meter HH2 and soil moisture sensor SM200 (Delta-T Devices Ltd., Cambridge, UK).

Persistence of water repellency was measured with water drop penetration time (WDPT) test. The WDPT test involves placing a 58 ± 5 μL drop of water from a medicine dropper on a soil from a standard height of 10 mm above the surface and recording the time taken for its complete penetration (Doerr et al. 2000).

Field measurements of infiltration through the use of the minidisk (4.5 cm in diameter) infiltrometer (Decagon 2007), under a negative tension $h_0 = -2$ cm were performed ca. 1.5 m beside the place where neutron probe experiment was done. Prior to the measurements, the litter layer was removed gently to prevent disturbance of the mineral soil. The cumulative infiltration I was assumed to be expressed by the Philip infiltration model (Philip 1957):

$$I = C_1 t^{1/2} + C_2 t + C_3 t^{3/2} + \ldots + C_m t^{m/2} + \ldots \quad (1)$$

where C_1, C_2, C_3, …, and C_m are coefficients, and t is time.

The sorptivity $S(h_0)$ was estimated from the first term of this eq. ($I = C_1 t^{1/2}$):

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

Equation (2) 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 (Iovino et al. 2018). It should be mentioned that the water sorptivity is a measure of both the SWR and soil pore size, while the ethanol sorptivity is a measure of soil pore size only (Hallett 2008).

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

$$k(h_0) = C_2/A \quad (3)$$

where A is a dimensionless coefficient.

Equation (3) 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).

The repellency index RI was calculated from all possible combinations of the measured values of water sorptivity, $S_w(-2$ cm$)$, and ethanol sorptivity, $S_e(-2$ cm$)$ using the method by Pekárová et al. (2015):

$$RI = 1.95 S_e(-2 \ cm)/S_w(-2 \ cm) \quad (4)$$

Infiltration experiments were accomplished at two 100 cm × 100 cm cells (one infiltrometer per site). First, the grass and herbs were mown and four steel infiltration frames (with 100-cm width and 30-cm height) were inserted into the soil to a depth of about 20 cm, forming the infiltrometer. In each of these infiltrometers, four steel access tubes w_1–w_4 (with the inner diameter of 4.3 cm and length of 200 cm) were inserted vertically into the holes made with an auger, see in Fig. 1a. 50 mm of water was applied manually with a watering can at a rate of about 2 mm min⁻¹, and the application took 50 min. The volumetric soil water content (m³ m⁻³) was measured in every 10 cm between 0 and 100 cm using the neutron moisture meter with Americium - Beryllium probe (Holdsworth 1970) before and after watering.

The penetration depth of water z_{max} was estimated as maximal depth of soil (soil layer) where the difference in volumetric water content measured prior and after irrigation was registered, i.e., where $(\theta_{I \ 50mm} - SD) > (\theta_{I \ 0mm} + SD)$. Location of the tubes in the infiltrometer and the influence spheres for $\theta = 0.2$ (m³ m⁻³), demarcated with dashed circles, are presented in Fig. 1a. The radius of influence r (cm) (equal to the radius of the spherical cloud containing 95% of neutrons retarded by the soil) as a function of volumetric soil water content (m³ m⁻³) was calculated from equation (Sumner 1999):

$$r = 15 \ (1/\theta)^{1/3} \quad (5)$$

Measured neutron counting rates, CR, were transformed to the volumetric soil water content (m³ m⁻³), using eq. (6)
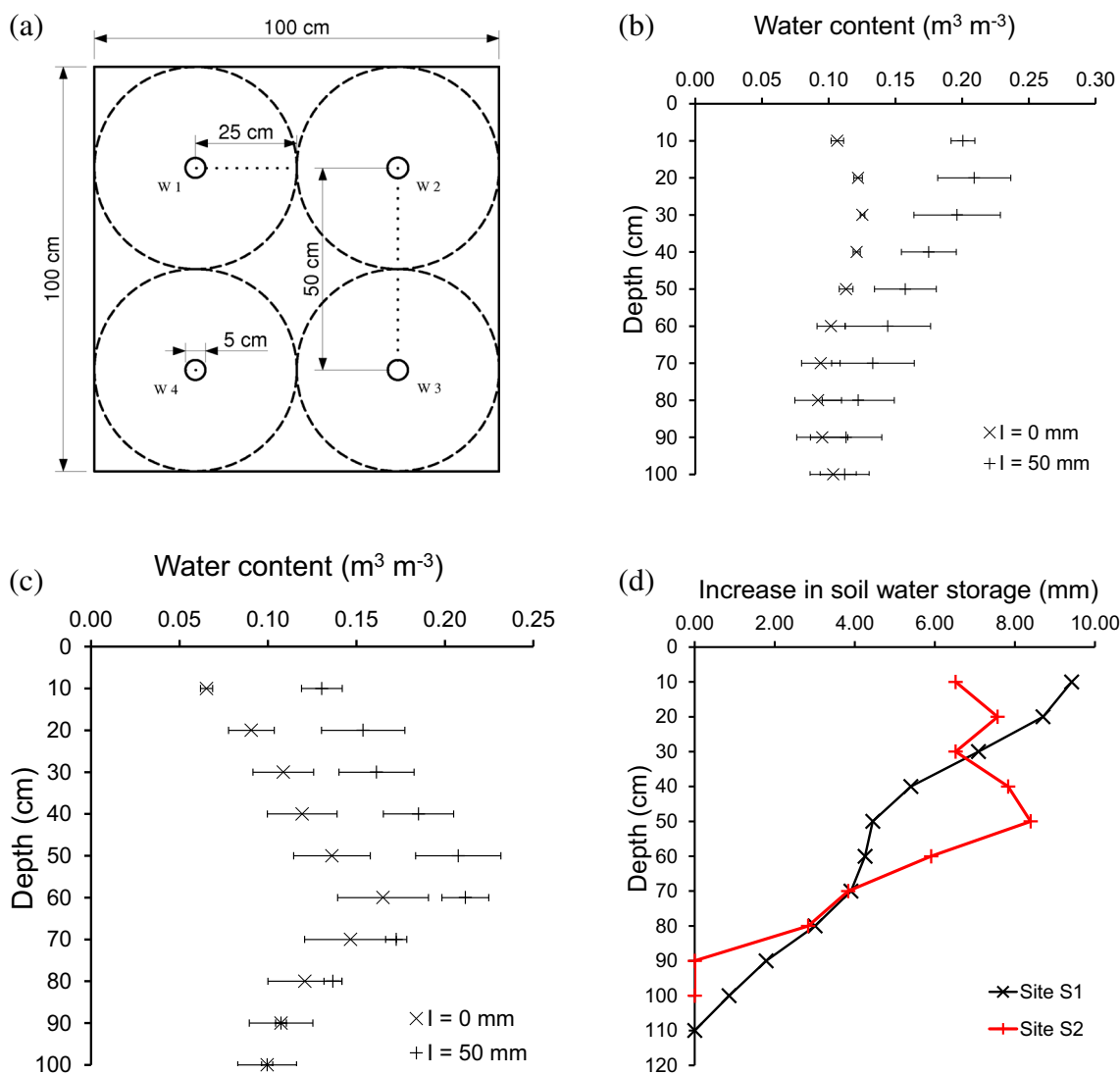
Fig. 1 Infiltrometer instrumentation and results of experiments at sites S1 and S2 near Sekule (Slovakia). (a) Location of steel access tubes (w1–w4) for measuring the volumetric soil water content, θ, (m³ m⁻³), using neutron moisture meter, with the influence spheres for θ = 0.20 (m³ m⁻³) demarcated with dashed circles. Soil water content (mean values with standard deviations) at sites S1 (b) and S2 (c) before (×, I = 0 mm) and after (+, I = 50 mm) irrigation. (d) Increase in soil water storage (mm) at sites S1 and S2 after application of 50 mm of water

obtained from our former calibration (Nagy et al. 2018) using gravimetric method:

$$\theta = 0.001145CR + 0.001722c \qquad (6)$$

where c is clay content (%).

Statistical analysis

Differences between the parameters estimated in different sites were evaluated using Welch's t-test. It is an adaptation of Student's t test, and is more reliable when the two samples have unequal variances and/or unequal sample sizes.

Welch's t-test defines the statistic t by the following equation:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\dfrac{s_1^2}{N_1} + \dfrac{s_2^2}{N_2}}} \qquad (7)$$

where $\overline{X}$, s, N and are the sample mean, sample variance and sample size, respectively.

The statistical significance in the analysis was defined at $p < 0.05$.

Results and discussion

Physical and chemical properties of the top-soils (0–10 cm), taken from the experimental sites S1 (native grassland species cover) and S2 (synanthropic grassland species cover) near Sekule, Slovakia, are presented in Table 1. It was found that both the organic carbon content and thickness of organic layer are higher at site S2 compared to S1. Higher organic matter content on the S2 site is the legacy of the agricultural use of this area. The content of organic matter was increased by fertilization and decomposition of crop residues.

Soil water content in upper 5 cm of soil profile, water drop penetration time, WDPT, hydraulic conductivity, $k(-2\ cm)$, sorptivity of both water, $S_w(-2\ cm)$, and ethanol, $S_e(-2\ cm)$, and repellency index, RI, prior to infiltration experiment, are shown in Table 2. Long hot and dry spell resulted in a low actual volumetric soil water content at both sites. Greater mean value of actual soil water content of top-soil was measured at S2, due to higher C_{org}. Higher C_{org} at S2 compared to S1 resulted also in greater values of parameter RI and lower values of sorptivity of water, $S_w(-2\ cm)$ and hydraulic conductivity, $k(-2\ cm)$. Mean value of WDPT at S1 was paradoxically higher than that at S2, probably due to the smaller mean value and range (difference between the lowest and highest values) of actual water content of top-soil at S1. Statistical evaluation of differences between the parameters estimated at S1 and S2 revealed significant differences in $S_w(-2\ cm)$, and RI, only.

Infiltrometer instrumentation and results are shown in Fig. 1. Mean values and standard deviations of soil water content along the soil profile, measured at sites S1 and S2 before and after application of a cumulative infiltration volume $I = 50$ mm are presented in Fig. 1b and c. After application of 50 mm of water, the penetration depth of water z_{max} was >100 cm at S1 and 90 cm at S2, i.e., it increased in the order: S2 < S1.

Patterns of water storage at both sites are quite different. The pattern at the site S1 is uniform, the mean values of water storage decreased relatively evenly (it can be said proportionally) from the maximal value (9 mm) in the upper 10 cm to the minimum in the depth of 110 cm of the soil profile. The shape of pattern at the S2 is different and irregular. Increase of water storage in the upper part of profile (to the depth of 40 cm) oscillates around value

of 7 mm, and then it reaches a maximum (9 mm) at a depth of 50 cm. From the depth of 60 cm, the water storage drops evenly to a depth of 90 cm. Although the patterns of water storage had a different shape (Fig. 1d), the cumulative increase in soil water storage in the depth of 0–50 cm at the site S1 and S2 was nearly the same (35.1% and 36.8% of applied water, respectively). According to the results presented in Table 2 and Fig. 1 we can state that grasslands at sites S1 and S2 have different soil water repellency parameters and shape of moisture pattern, induced probably by finger flow. Nevertheless, the soil water retention capacity of site S2, formed by spontaneous secondary succession is nearly the same as the retention capacity of native grassland S1.

The soil water content along soil profile measured during this study is different from the patterns measured after an application of 62 and 112 mm of water at non-tilled plots with sandy loam soil covered with grassland in Zábrod (in mountainous area of the Šumava, Czech Republic) (Lichner et al. 2014) and at 3 plots with sandy loam soil under sunflower within an experimental site near Kalinkovo village of southwest Slovakia (Nagy et al. 2018). Differences in measured soil water content and various shapes of moisture patterns along the soil profiles in previously mentioned studies were indicators and/or were caused by the typical soil parameters (for example particle size distribution and organic carbon content), different development of soil horizons, different vegetation cover with root system and ongoing tillage operations or soil degradation.

The soils at both sites belong to Arenosol group, which are sandy-textured soils that lack any significant soil profile development. It means that soil profiles at both sites are homogenous to the depth of 2 m with very similar physical parameters; so we assumed that the greatest effect on the measured soil water content patterns was due to the different type of vegetation and/or uneven wetting (finger flow) induced by soil water repellency.

According to Fiala (2001), *Calamagrostis* is expansive species, which forms larger root system located deeper in the soil and this is the reason why could be more successful in the competition for soil nutrients and also has greater competitive ability including more efficient use of soil water, thereby inhibiting establishment, survival, and reproduction of native species.

Table 1 Physical and chemical properties of the top (0–10 cm) soils taken from the experimental sites S1 (native grassland species cover) and S2 (synanthropic grassland species cover) near Sekule, Slovakia

Site	Sand (%)	Silt (%)	Clay (%)	Thickness of organic layer (cm)	CaCO₃ (%)	C_{org} (%)	pH (H₂O)	pH (KCl)
S1	88.45	7.35	4.20	2	<0.05	6.60	5.20	4.28
S2	91.30	2.80	5.90	10	<0.05	9.90	5.14	3.91

Table 2 Soil water content, θ, in the upper 5 cm of soil profile, water drop penetration time, WDPT, hydraulic conductivity, $k(-2\ \text{cm})$, sorptivity of both water, $S_w(-2\ \text{cm})$, and ethanol, $S_e(-2\ \text{cm})$, and repellency index, RI, at the sites S1 and S2 near Sekule prior to infiltration experiment. Arithmetic means with the same letter are not significantly different (Welch's unequal variances t-test at $\alpha < 0.05$)

Site	Attribute	Minimum value	Maximum value	Arithmetic mean	Standard deviation	Variance	Skewness	N
S1	θ (m^3 m^{-3})	0.0010	0.0130	0.00450 [a]	0.00428	1.83×10^{-5}	1.00	8
	WDPT (s)	120	4500	1723 [a]	1610	2.59×10^6	0.29	12
	$k(-2\ \text{cm})$ (m s^{-1})	4.05×10^{-6}	9.42×10^{-5}	3.50×10^{-5} [a]	3.66×10^{-5}	1.34×10^{-9}	0.84	5
	$S_w(-2\ \text{cm})$ (m s$^{-1/2}$)	1.14×10^{-3}	3.77×10^{-3}	2.39×10^{-3} [a]	1.10×10^{-3}	1.22×10^{-6}	0.12	5
	$S_e(-2\ \text{cm})$ (m s$^{-1/2}$)	4.27×10^{-4}	2.23×10^{-3}	1.14×10^{-3} [a]	6.77×10^{-4}	4.6×10^{-7}	0.80	5
	RI (−)	0.993	17.2	5.427 [a]	4.021	16.17	1.46	25
	z_{max} (cm)	90	110	105 [a]	10	100	−1.16	4
S2	θ (m^3 m^{-3})	0.0023	0.0234	0.01016 [a]	0.00756	5.72×10^{-5}	0.60	10
	WDPT (s)	1	6883	664 [a]	1728	2.99×10^6	3.19	16
	$k(-2\ \text{cm})$ (m s^{-1})	1.25×10^{-6}	8.13×10^{-5}	1.80×10^{-5} [a]	2.06×10^{-5}	4.26×10^{-10}	2.18	14
	$S_w(-2\ \text{cm})$ (m s$^{-1/2}$)	3.60×10^{-5}	1.28×10^{-3}	3.42×10^{-4} [b]	3.42×10^{-4}	1.17×10^{-7}	1.27	16
	$S_e(-2\ \text{cm})$ (m s$^{-1/2}$)	9.97×10^{-4}	5.66×10^{-3}	2.85×10^{-3} [a]	1.82×10^{-3}	3.31×10^{-6}	0.18	11
	RI (−)	1.52	306.7	57.73 [b]	77.30	5975.30	1.68	176
	z_{max} (cm)	70	100	90 [a]	14.14	200	−0.82	4

Conclusions

Higher organic carbon content at the site with synanthropic vegetation compared to the site with native vegetation resulted in smaller values of hydraulic conductivity, $k(-2\ \text{cm})$, and sorptivity of water, $S_w(-2\ \text{cm})$ and greater values of measured soil water repellency parameter RI. Evaluation of differences between the hydrophysical and soil water repellency parameters estimated in S1 and S2 using Welch's test of means revealed that the differences in sorptivity of water, $S_w(-2\ \text{cm})$, and repellency index, RI, only were statistically significant at $p < 0.05$. Infiltration experiments showed slightly different distribution of water across the depth of soil profile at these sites; however, the cumulative increase in soil water storage in the depth of 0–50 cm was nearly the same.

According to the results presented in Table 2 and Fig. 1 we can state that grasslands at sites S1 and S2 have different soil water repellency parameters and shape of moisture pattern across the soil profile, induced probably by finger flow. Nevertheless, for the experimental conditions investigated, the water retention capacity of spontaneously recovered grassland is nearly the same as the retention capacity of native grassland. These first results suggest that spontaneous succession may be an appropriate tool for maintaining hydroecological functions of abandoned sandy fields in studied locality, but further research is necessary.

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