



The relations between soil hydrophobicity and vegetation in abandoned arable fields on sandy soil

Edyta Hewelke¹ · Piotr T. Zaniewski² · Artur Pędziwiatr³ · Dariusz Gozdowski⁴ · Ewa B. Górską⁵

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Abstract

The study aimed to find the significant relations between the dominant plant species of secondary succession of lasting abandonment of agricultural fields on sandy soil in central Poland, and soil water repellency strength. The critical soil moisture content for hydrophobicity for individual sites ranged from 10.7 to 16.7%, and the differences were not statistically significant. After periods of prolonged drought, all abandonment agriculture fields indicated lower soil moisture content than critical threshold (10.7–16.7%) for soil water repellency. The soil water repellency was assessed as extreme class based on Water Drop Penetration Time (WDPT) test. The relationship between the main dominant species cover and WDPT test was diverse, with *Agrostis gigantea* agg. and *Avena sativa* as a species reaching highest cover within low values of WDPT. Inexpertly *Betula pendula* agg. (unexpectedly) and *Pinus sylvestris* dominated sites with the highest values of WDPT test. The conducted research indicates that due to climate change, leaving sandy soils in warm temperate climate without an alternative management plan may pose a significant environmental risk.

Keywords Climate change · Dry periods · Sandy soil · Soil water repellency

Introduction

Soil water repellency (SWR) is a natural phenomenon presenting a degree of affinity of the analyzed soil surface to absorb water and persist from a few seconds to a few hours, or even longer period (King 1981). SWR decays with time, and the direct and indirect consequences are a concern not only during the timescale at which the water repellency persists. The reason for the occurrence of SWR may be the

properties of the soil organic matter (SOM) or the water-repellent organic cover on soil particles, which, under the influence of given factors, such as soil moisture content, temperature, soil texture, microbiological activity, or chemical properties of the soil, may change its intensity (Doerr et al. 2000). Fungal biomass and lipid fraction have been identified as significant factors influencing the presence and persistence of SWR in forest soils (Lozano et al. 2013).

The plant cover largely contributes to the development of SWR as a source of hydrophobic compounds found in surface and near-surface soils. Growing trend in publishing papers related to the linkage between SWR and plant (Popović and Cerdà 2023) suggests that certain vegetation types, and even different plant species, are frequently associated with severe SWR occurrence. SOM content has a meaningful impact on the soil water regime, and soil moisture affects SOM transformation, accumulation, and the associated climatic feedback (Goebel et al. 2011). Covering vegetation as the main source of SWR-induced compounds affects the distribution of SWR in the field. Additionally, SWR is affected by the chemical reaction of SOM on the soil particle surface. Diehl (2013) explained that

✉ Edyta Hewelke
edyta_hewelke@sggw.edu.pl

¹ Department of Environmental Development, Institute of Environmental Engineering, Warsaw University of Life Science, Warsaw, Poland

² Department of Forest Botany, Institute of Forest Sciences, Warsaw University of Life Science, Warsaw, Poland

³ Department of Soil Science, Institute of Agriculture, Warsaw University of Life Science, Warsaw, Poland

⁴ Department of Biometry, Institute of Agriculture, Warsaw University of Life Science, Warsaw, Poland

⁵ Department of Biochemistry and Microbiology, Institute of Biology, Warsaw University of Life Science, Warsaw, Poland

hydrolysis-condensation reactions of ester and deprotonation of carboxylic and phenolic groups in SOM can increase soil wettability.

SWR is a widespread phenomenon that involves altered hydrological (Gall et al. 2024) and geomorphological processes. Global climate change like drought, warming, heat waves, and heavy rainfall, and SWR is considered as a potential factor causing soil erosion, preferential flow path, revealing that water-repellent soil may have a high risk of water loss, nutrient leaching, and contaminant (Doerr et al. 2000), which means the degradation to impact whole ecosystems. SWR has been observed by (Wang et al. 2021) to decrease summer maize growth, particularly when the initial persistence of SWR is high, affecting soil water content, evaporation, and root water uptake. Lowe et al. (2019) point out SWR limits plant available water, leading to decreased crop yields, making it a concern for agricultural production. A study on ecological farming (Fér et al. 2020) mostly positively influenced the soil's physical properties, but increased SWR. On the other hand, adding very strongly and extremely water-repellent biochar presented by Šurda et al. (2024) induced slight severity of water repellency and did not induce persistence of SWR in the biochar-soil mixture. According to the results presented by Šurda et al. (2020) on an early stage of primary and secondary succession grasslands have different SWR parameters and shape of moisture patterns across the soil profile, induced probably by finger flow.

In connection with the progressing warming of the climate and the increasing frequency of droughts, it can be assumed that SWR will increasingly strongly affect the hydrophysical properties of soils and mineralization of organic carbon in areas characterized by a warm temperate climate. Studies (Hewelke et al. 2022) on abandoned agricultural land indicate a longer-lasting and more substantial SWR in warm temperate climate than in Mediterranean regions with a warmer climate.

The dynamic interrelationships and feedback loops (Doerr et al. 2000; Goebel et al. 2011) that are linked to SWR occurrence require the consideration of several variables involved in the development of SWR: vegetation, climates, soil types, hydrological processes, and management in natural and agroecosystems (Smettem et al. 2021). Vegetation and its succession can change the parameters of SWR (due to the change in the amount and composition of soil organic matter). Studies in Germany, Hungary, and Slovakia (Lichner et al. 2018), which were tested in natural and agricultural environments indicate that dynamics of SOM composition during the succession controls SWR. Studies of soil water repellence in soils from New Zealand evidenced that soil with relatively low content (< 2%) of soil organic carbon is characterized by the lower water repellence compared to soil with the content of soil

organic carbon amounting to 4% (Fu et al. 2021). Furthermore, several studies also demonstrated that some soil water repellency parameters can be predicted from the content of SOM in soils using models like Langmuir-type model (Fu et al. 2021; Wijewardana et al. 2016). Relatively high content of TOC in young birch stands is rather not common since Jonczak et al. (2023) demonstrated that low-molecular humus fractions are susceptible to microbial degradation in young birch stands. Therefore, the loss of TOC can be observed in surface A horizons in young birch stands. However, the study also revealed that TOC can be stored in A horizons in next steps of birch succession, accompanied by the maturity of humic acid (Jonczak et al. 2023). Other factors like rate of litter decomposition (i.e., high content of polyphenols retard decomposition), N content in litter and soil, and microbial species affect the storage of carbon in soils and thus soil water repellency (Albers et al. 2004; Prescott 2010; Wu et al. 2024). Fluorescence investigation on humic substance structure (Mielnik et al. 2021) proved the predominance of simpler fulvic-like structures in humic acid (HA) extracted from the hydrophobic, abandonment soil with pine succession, which indicated a relatively low molecular weight or a smaller number of chromophores with conjugated double bonds, and a lower humification degree of HA compared to cultivated land. The abandonment of agricultural lands leads to changes in soil properties, with an increase in SWR parameters such as water drop penetration time (WDPT) and repellency index (RI) (Lichner et al. 2020, 2023). Research presented by Whelan et al. (2015) shows that temperature and humidity influence the breakdown of water repellency, with contact angle measurements decreasing with time and increasing with stearic acid concentration. Additionally, sandy soils are more sensitive to climate change and human activities compared to other soils (Huang and Hartemink 2020).

The literature review provides insights into the impact of land abandonment on SWR and its strength, but there is no direct discussion of the relationship between SWR and the abandonment of the agricultural fields and the succedent of plant species.

The proposed research is directed towards determining plant species and their relation to SWR. The aim of this study was to find the significant relations between the dominant plant species of secondary succession, during 10–27 years of lasting abandonment of agricultural fields on sandy soil, and SWR strength. We hypothesized that during dry periods the risk occurrence of SWR increases, given special conditions, prolonged natural processes, and complex interactions (in warm temperate climate on various physical, chemical, and biological processes in the sandy soils) we can detect the cause of SWR based on the plant-SWR relations.

Material and methods

Sites description

Seven sites near the village Stanisławów (52°17'N; 21°31'E) in the Mazovian lowlands, central Poland, were selected. Climate according to Kottek et al. (2006), is classified as warm temperate (Cfb), with an annual rainfall of 545 mm, and average annual temperature of 7.8 °C. For many generations, traditional extensive agriculture has dominated here on small farms with an area of 5–8 ha, usually consisting of several plots. In the 1970s, a network of drainage ditches was dug to improve water content in arable fields whose aim was to increase production potential. However, at the end of the 1980s, agricultural production was limited or discontinued due to the low production potential of sandy soils. The experimental sites were selected to include three different stages of secondary succession, i.e., a Scots pine forest and a birch forest, almost 30 years old (1.2–1.5 ha) and extensive arable usage in the relatively same site conditions i.e., climate, soil and relief conditions. Three sites were surveyed in 2020 and four were surveyed in 2023 (Fig. 1). The year 2023 was the second and 2020 the

third warmest compared to the multi-annual analyzes of 1971–2023 for the Masovian region, i.e. in 2019 annual average was 10.98 °C, 2023 – 10.68 °C, 2020 – 10.53 °C. For example four consecutive months in 2023 – June, July, August and September – had temperatures above normal for July (the warmest month of the year). Despite higher average rainfall in 2023 – 572.0 mm, and in 2020 – 645.5 mm compared to the multiannual period, drought was noticeable.

Fieldworks

Vegetation was described in the middle of the vegetation period with 100 m² relèves according to the Braun-Blanquet's (1964) approach, using Barkman et al. (1964) scale. Cryptogams were included in the survey (Table S1). Vegetation sites were described (Table 1) according to the European reference classification of vegetation (Mucina et al. 2016). In further analyses, *Betula pendula* agg. and its hybrid with *B. pubescens*, and *Agrostis gigantea* and its hybrid with *A. stolonifera* were merged into aggregates. Cover was used as a measure of species abundance, as pure cover scales are preferred in ecological studies (Barkman et al. 1964; Dengler et al. 2008).

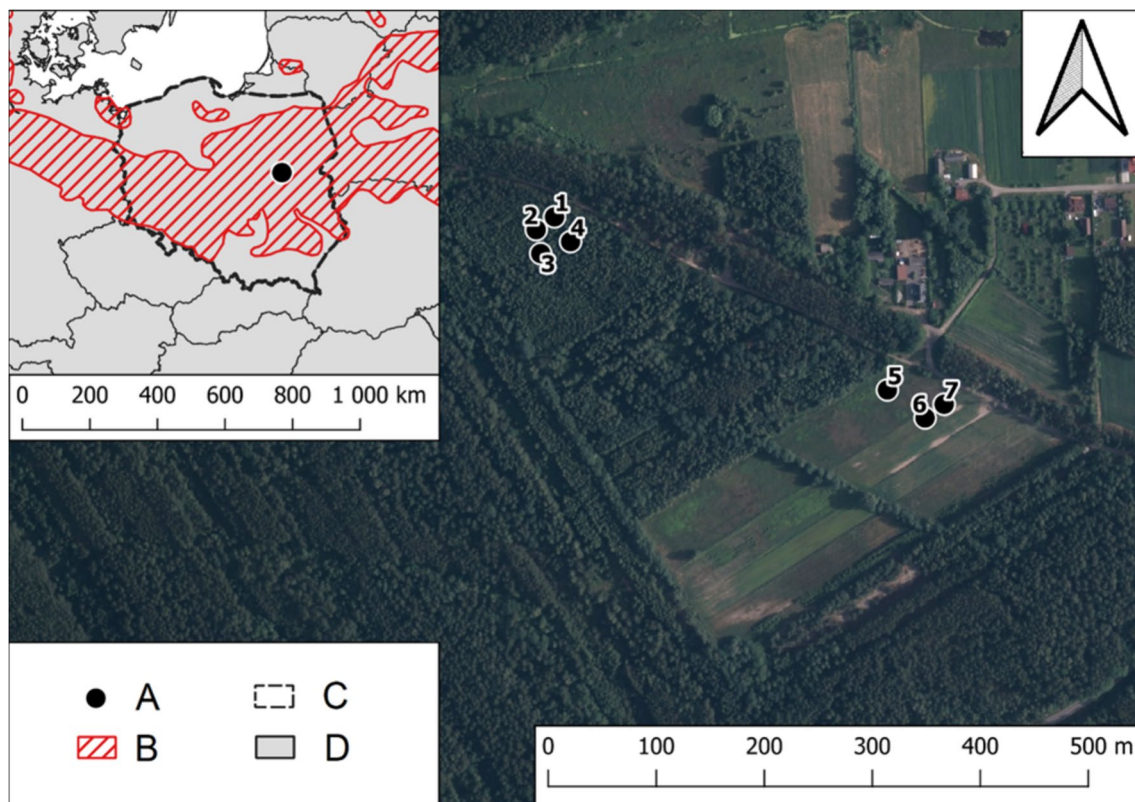


Fig. 1 Location of the study sites: **A** study sites (1–7 described in Table 1), **B** European Sand Belt (Zeeberg 1998), **C** Poland, **D** borders of adjacent Countries

Table 1 Description of the sites surveyed in the vicinity of Stanisławów village, central Poland (E₃ – tree layer, E₂ – shrub layer, E₁ – herb layer, E₀ – bryophyte layer)

No	Date	Vegetation type	Short description of vegetation
1	2020	young birch stand (<i>Molinio-Frangulion</i>)	Woodland: E ₃ : <i>Betula pendula</i> agg., E ₂ : <i>Frangula alnus</i> , <i>Sorbus aucuparia</i> , E ₁ : <i>Juncus effusus</i> , <i>Rubus</i> sect. <i>Rubus</i>
2	2023	young birch stand (<i>Molinio-Frangulion</i>)	Woodland: E ₃ : <i>Betula pendula</i> agg., E ₂ : <i>Frangula alnus</i> , E ₁ : <i>Agrostis gigantea</i> agg., <i>Juncus effusus</i> , <i>Rubus</i> sect. <i>Rubus</i> , E ₀ : <i>Brachythecium rutabulum</i> , <i>Pleurozium schreberi</i>
3	2020	young pine forest (<i>Dicrano-Pinion sylvestris</i>)	Woodland: E ₃ : <i>Pinus sylvestris</i> , <i>Betula pendula</i> agg., E ₂ : <i>Frangula alnus</i> , E ₁ : <i>Agrostis gigantea</i> agg., <i>Holcus mollis</i> , E ₀ : <i>Hylocomium splendens</i> , <i>Pleurozium schreberi</i>
4	2023	young pine forest (<i>Dicrano-Pinion sylvestris</i>)	Woodland: E ₃ : <i>Pinus sylvestris</i> , <i>Betula pendula</i> agg., E ₁ : <i>Agrostis gigantea</i> agg., <i>Pilosella officinarum</i> , <i>Rumex acetosella</i> , E ₀ : <i>Dicranum polysetum</i> , <i>Pleurozium schreberi</i>
5	2023	community with <i>Pilosella officinarum</i> (initial <i>Armerion elongatae</i>)	Initial meadow: E ₁ : <i>Achillea millefolium</i> , <i>Agrostis gigantea</i> agg., <i>Arrhenatherum elatius</i> , <i>Carex ovalis</i> , <i>Festuca rubra</i> , <i>Holcus lanatus</i> , <i>Hypochoeris radicata</i> , <i>Juncus effusus</i> , <i>Luzula campestris</i> , <i>Pilosella officinarum</i> , <i>Rumex acetosella</i> , E ₀ : <i>Polytrichum juniperinum</i> , <i>Polytrichum piliferum</i>
6	2020	extensive arable field (<i>Scleranthion annui</i>)	Arable field: E ₁ : <i>Agrostis gigantea</i> agg., <i>Anthoxanthum aristatum</i> , <i>Holcus mollis</i>
7	2023	extensive arable field (<i>Scleranthion annui</i>)	Arable field: E ₁ : <i>Agrostis gigantea</i> agg., <i>Anthoxanthum aristatum</i> , <i>Avena fatua</i> , <i>Avena sativa</i> , <i>Digitaria ischaemum</i> , <i>Holcus mollis</i> , <i>Setaria pumila</i>

Soil sampling and laboratory analysis

The impact of land use changes and plant cover was analyzed in the topsoil mineral layer (after removing litter). The soil samples were collected in August 2020 and September 2023, after drying periods. The site's description was previously presented in Hewelke et al. (2022, 2023). The main properties, defined in the 0–5 cm of the upper mineral soil horizon of the Podzols (IUSS Working Group WRB 2022), are presented in Table 2. The particle size distribution was analyzed using the sieve and hydrometric methods (IUSS Working Group WRB 2022; Pansu and Gautheyrou 2006). Soil moisture retention characteristics were measured in a laboratory in triplicate on undisturbed soil samples (100 cm³) using a reference method (Klute 1986). The soil moisture content values between pF 0.4 and 2.0 were determined in a standard sandbox. The amounts of water at pF 2.3, 2.7, 3.0, and 4.2 were measured in pressure chambers, and more

details concerning the methodology are presented in a previous study by Hewelke (2019). Soil pH was measured potentiometrically in soil suspensions with 1 M KCl in the ratio of 1:2.5 (w/v) using pH-meter CP-505 (Elmetron). Total organic carbon (TOC) and total nitrogen (TN) contents were measured with a Vario Max Cube CN Elemental analyzer. The TOC content, the C/N ratio, and pH values are balanced within the studied sites, indicating that post-agricultural soils were cultivated and fertilized for a long time.

Soil water repellency assessment

SWR was determined using the most suitable and widespread test (Doerr et al. 2000; Dekker et al. 2009), water drop penetration time (WDPT) test. As recommended by Ziogas et al. (2005) SWR was measured on samples taken in the field under dry conditions to reveal and determine the highest persistence of SWR that might occur in

Table 2 Basic soil physical and chemical properties

Site no	Particle size distribution			BD (bulk density) kg m ⁻³	FWC (full water capacity) m ³ m ⁻³	Θ pF 2 m ³ m ⁻³	Θ pF 4.2 m ³ m ⁻³	TOC %	TN %	TOC/TN ratio	pH (KCl)
	Sand (%)	Silt (%)	Clay (%)								
1	97	2	1	1319	0.472b	0.198ab	0.105b	2.26 cd	0.15b	14.88d	3.78c
2	90.5	7.5	2	1198	0.427a	0.227b	0.079a	2.46d	0.16b	15.35d	3.51a
3	97	2	1	1310	0.422a	0.204b	0.070a	2.23 cd	0.20c	11.43a	3.93d
4	93	4	3	1306	0.430a	0.198ab	0.074a	1.82b	0.12a	14.73 cd	3.80c
5	93	6	1	1544	0.432a	0.187ab	0.070a	1.55a	0.12a	13.02b	3.61b
6	95	3	2	1317	0.489b	0.201ab	0.100b	2.10c	0.15b	13.87bc	3.78c
7	92.5	4.5	3	1286	0.475b	0.155a	0.079a	1.74ab	0.12a	14.76d	3.52a

Different letters indicate statistically significant differences ($n=3$) according to analysis of variance and the Fisher procedure of multiple comparisons ($p < 0.05$).

the field. To determine the actual SWR value triplicate samples of about 20 g of soil were placed in Petri dishes and 10 drops (the volume of water in a droplet was equal to 60 μL), using a standard medicine dropper. According to the classification of SWR proposed by Dekker and Jungerius (1990) and Bisdorf et al. (1993), i.e.: wettable or non-water-repellent soil ($\text{WDPT} < 5$ s), slightly ($\text{WDPT} = 5\text{--}60$ s), strongly ($\text{WDPT} = 60\text{--}600$ s), severely ($\text{WDPT} = 600\text{--}3600$ s), and extremely ($\text{WDPT} > 3600$ s) water repellent soil, the mean values of the WDPT test were used to assess the SWR class.

Indicating the relationship between soil moisture content and SWR, the WDPT test was performed for different moisture contents. The value 8 h was used as a limit for WDPT test observations. On 100 cm^3 undisturbed soil samples, in triplicate, starting from full water capacity, that had been adjusted by equilibrating the material at different pF levels (i.e., 2.0, 2.3, 2.7, 3.0, 3.3, 3.7, 4.2) WDPT was used. The detailed procedure is described in Hewelke (2019).

Statistical analysis

Statistical analysis of soil properties was performed by analysis of variance and the Fisher procedure of multiple comparisons, $p < 0.05$, using Statistica Software (version 13, StatSoft Inc., Tulsa, OK, USA, 2011). The species data was arithmetically transformed (Tüxen and Ellenberg 1937), using the mean of cover intervals. The covers of the same species, belonging to subsequent vegetation layers, were merged. Only dominant species that appeared with more than 10% cover with at least one site, were used in further analyzes. The canonical correspondence analysis (CCA) was performed. The WDPT value was used as an environmental variable. The significance of the species-environment relation was checked with a Monte Carlo test (9999 permutations). In addition, the set of generalized linear models (GLM) was performed for WDPT, together with response curves for each dominant species, using the

forward selection procedure, Poisson distribution, and log link function (Šmilauer and Lepš 2014). CCA and GLM analyzes were performed with Canoco 5 software (ter Braak and Šmilauer 2012).

Results and discussion

Soil water repellency assessment

The indicated critical threshold soil moisture (Crit Θ) for water repellency was established in laboratory conditions (Fig. 2). The soil water moisture when the SWR appeared was close to field water capacity (pF value equal 2.3–3.0). The previous study (Hewelke et al. 2022, 2023) confirmed that laboratory tests reflected well the occurrence of SWR in field conditions. The values reached for each study site were compiled in Table 3. There were no significant differences between the sites and the critical threshold was recognized in all studied samples, as the limit between 0.107 to 0.167 $\text{m}^3 \text{m}^{-3}$. The variability in Crit Θ values can be found concerning the land use of sand i.e., 2% for dune (Dekker et al. 2001), 9.3–15% for agricultural fields (Ziogas et al. 2005), for extensive arable soil 9–10%, for abandoned agriculture soil 14–16% (Hewelke 2019). The actual soil moisture content measured for all sites in these selected dates was below the critical moisture value for SWR. The lowest value of soil moisture content was detected at the *Dicrano-Pinion sylvestris* site (no 3), where the highest SWR strength was parallel perceived. Moreover, extremely repellent classes were detected in six sites, one site in extensive arable usage was classified as strongly repellent. The values of WDPT tests obtained for young birch stands (*Molinio-Frangulion*) are surprisingly high. The laboratory measurements of contact angle (CA) values on the same dry soil material from 2020 were presented by Hewelke et al. (2023), and the high mean value of the wetting CA was equal to 114.2°. It turns out that if the habitat is over-dry, the extreme SWR class can be expected.

Fig. 2 pF curves for post-arable land sites (Site 1–5) and under extensive arable sites (Site 6–7) together with the critical threshold soil moisture (Crit Θ) for seven sites, horizontal blue shadowed box

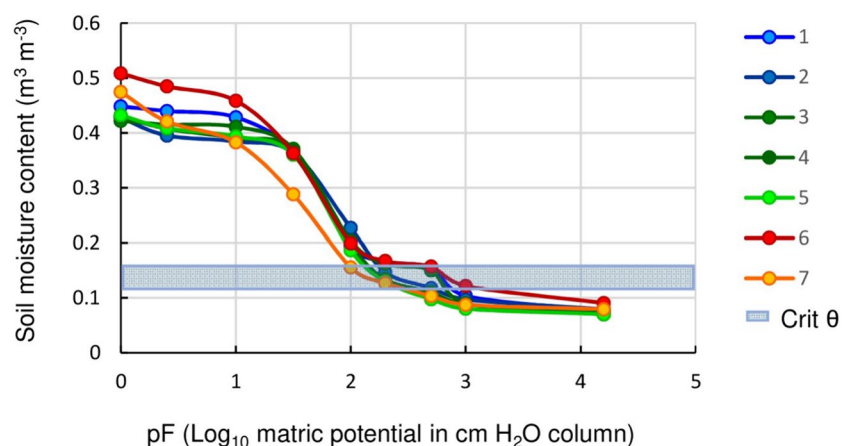


Table 3 Soil water repellency indicators (means $\pm$ standard deviations)

Site no	Critical θ (m ³ m ⁻³)	Actual θ (m ³ m ⁻³)	WDPT (s)	Repellency Class
1	0.139a $\pm$ 0.013	0.061ab $\pm$ 0.004	19080e $\pm$ 1867	Extremely repellent
2	0.147a $\pm$ 0.018	0.116d $\pm$ 0.036	18000de $\pm$ 3275	Extremely repellent
3	0.150a $\pm$ 0.017	0.031a $\pm$ 0.002	28800f $\pm$ 0	Extremely repellent
4	0.134a $\pm$ 0.023	0.070bc $\pm$ 0.010	17160d $\pm$ 3900	Extremely repellent
5	0.130a $\pm$ 0.018	0.078bc $\pm$ 0.017	7950b $\pm$ 763	Extremely repellent
6	0.138a $\pm$ 0.010	0.049ab $\pm$ 0.003	10980c $\pm$ 1727	Extremely repellent
7	0.127a $\pm$ 0.020	0.094 cd $\pm$ 0.021	227a $\pm$ 27	Strongly repellent

Different letters indicate statistically significant differences ($n=3$) between means according to analysis of variance and the Fisher procedure of multiple comparisons ($p < 0.05$)

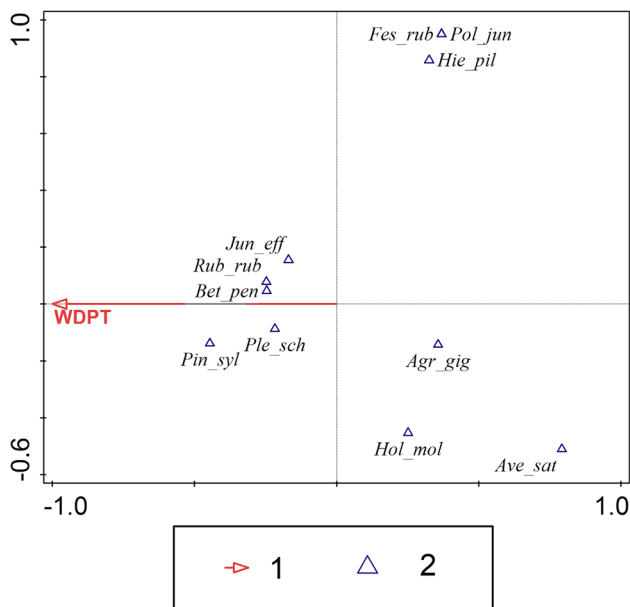


Fig. 3 The relationship between dominant species vegetation and WDPT (CCA) in the studied sites near Stanisławów village, central Poland: 1 – environmental variable, 2 – species (*Agr_gig* – *Agrostis gigantea*, *Ave_sat* – *Avena sativa*, *Bet_pen* – *Betula pendula* agg., *Fes_rub* – *Festuca rubra*, *Hie_pil* – *Hieracium pilosella*, *Hol_mol* – *Holcus mollis*, *Jun_eff* – *Juncus effusus*, *Pin_syl* – *Pinus sylvestris*, *Ple_sch* – *Pleurozium schreberi*, *Pol_jun* – *Polytrichum juniperinum*, *Rub_rub* – *Rubus* sect. *Rubus*)

Plant species and SWR relations

The WDPT explanatory variable accounted for 26.3% of the total variation in CCA ordination (pseudo- $F=1.8$, p -value=0.038). The species especially connected with high WDPT values was *Pinus sylvestris*, while *Avena sativa* was associated with the low WDPT values (Fig. 3). Other species which were observed at high WDPT were *Pleurozium schreberi*, *Rubus* sect. *Rubus*, *Betula pendula* agg., *Juncus effusus*, while other species which were observed at low or moderate WDPT were *Festuca rubra*, *Polytrichum juniperinum*, *Hieracium pilosella*, *Agrostis gigantea* and *Holcus*

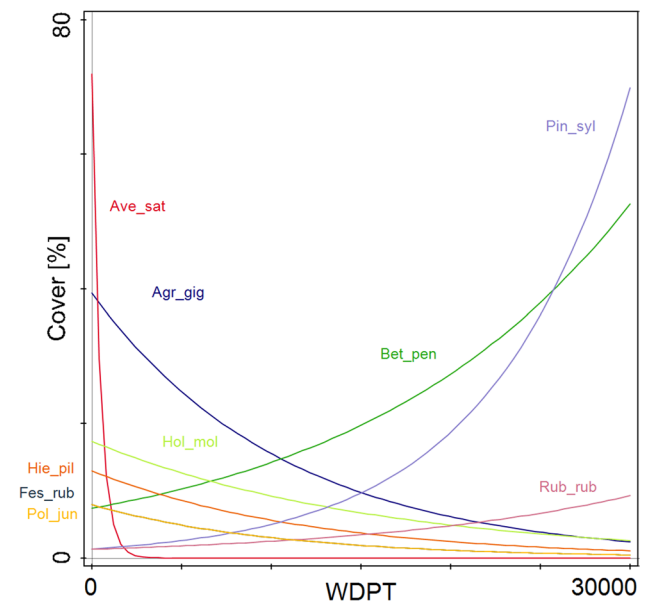


Fig. 4 Relationship between dominant species cover and WDPT in the studied sites near Stanisławów village, central Poland (GLM, Poisson distribution and log link function used, abbreviations explained in the Fig. 3)

mollis. The relationship between the main dominant species cover and WDPT was diverse, with *Agrostis gigantea* agg. and *Avena sativa* as a species reaching highest cover within low values of WDPT, and *Betula pendula* agg. and *Pinus sylvestris* dominated sites with the highest values of WDPT (Fig. 4). The response of *Juncus effusus* and *Pleurozium schreberi* turned out to be insignificant (Table 4).

Habitats dominated by Scots pine (*Pinus sylvestris*) are associated with severe to extreme SWR in different climate regions (Iovino et al. 2018; Benito et al. 2019; Chai et al. 2022). The presence and persistence of SWR under *Pinus* are influenced by various factors, including the relative concentrations of total free lipids in the soil, abundance and diversity of bacterial and fungal communities, and the quality of soil organic matter (Lozano et al. 2013; Šurda et al. 2021; Chai et al. 2022). In 100 years of Scots pine afforestation

Table 4 Summary of response of dominant species cover to WDPT value (GLM) within surveyed sites near Stanisławów village (central Poland)

Response	Predictor Form Type	R2 [%]	F	P
<i>Agrostis gigantea</i> agg	linear	63.7	56.5	< 0.001
<i>Avena sativa</i>	linear	100.0	170.3	< 0.001
<i>Betula pendula</i> agg	linear	18.7	45.4	0.001
<i>Festuca rubra</i>	linear	16.2	11.8	0.019
<i>Hieracium pilosella</i>	linear	14.7	16.6	0.010
<i>Holcus mollis</i>	linear	10.9	15.9	0.010
<i>Pinus sylvestris</i>	linear	44.0	115.7	< 0.001
<i>Polytrichum juniperinum</i>	linear	16.2	11.8	0.019
<i>Rubus</i> sect. <i>Rubus</i>	linear	11.1	8.0	0.036
<i>Juncus effusus</i>	linear	4.3	4.26	0.094
<i>Pleurozium schreberi</i>	linear	9.6	5.64	0.064

(NE Spain) in a deforested area previously populated by a natural European beech forest in topsoils under pine showed a strong SWR intensity, while a slight SWR was found under the natural beech (Girona-García et al. 2018). During the hot and dry summer period in SW Slovakia, Šurda et al. (2021) found a similarity between unsaturated hydraulic conductivity and repellency index, vs. pine forest age relationships. The differences in soil hydrophysical properties (connected to SOC and WDPT relationships vs. pine forest age) were attributed to soil organic carbon content and vegetation-induced soil water repellency (pine needles site vs. grass cover/pine needles site). *Pinus sylvestris* is associated with severe to extreme SWR, influenced by factors such as microbial communities and soil organic matter. The presence of SWR in pine forests can have negative implications for water dynamics and plant growth.

SWR is influenced by the dominant vegetation, with *Betula pendula* agg. being associated with humid habitats, and no evidence of SWR connected with *Betula* was in literature found. However, changes connected with the warming climate require further investigation, taking into account the identification of hydrophysical soil properties in dry conditions of the habitat.

In the study of dune vegetation in the temperate oceanic climate of Netherlands, grass roots, including *Agrostis stolonifera* and *Festuca rubra*, were especially responsible for increased SWR comparing to *Quercus robur* (Mao et al. 2016). Pines are generally known to be associated with increased SWR, usually higher than for oaks (Popović and Cerdà 2023). In our study, the presence of *Agrostis gigantea* agg. (including its hybrid with *Agrostis stolonifera*) and *Festuca rubra* was associated with lower SWR than for pine and birch. Similarly, lower SWR in grassland dominated by *Calamagrostis epigejos* and *Agrostis tenuis* compared to 30-year-old pine stand was also registered in aeolian sandy

soils in the continental climate of Slovakia (Lichner et al. 2010). In addition, the cereal crops, including *Avena sativa*, were reported as less repellent than pasture species in the laboratory experiment with fired sand (McGhie and Posner 1981). One of the oldest remediation strategies is to select plant species that are naturally adapted to droughts and water-repellent soils and our research conducted suggests that especially *Avena sativa* and *Agrostis gigantea* agg. are promising species that can prevent the occurrence of SWR.

Conclusions

Hydrophobicity tests on sandy soil after periods of prolonged drought showed its occurrence in all selected sites. The critical soil moisture content for hydrophobicity for individual sites ranged from 10.7 to 16.7%, and the differences were not statistically significant. The highest WDPT test values were recorded for pine forest sites (*Dicrano-Pinion sylvestris*), and unexpectedly for birch sites (*Molinio-Frangulion*), with species *Pinus sylvestris* and *Betula pendula* agg. dominated, respectively.

The conducted research indicates that due to climate change, leaving sandy soils without an alternative management plan may pose a significant environmental risk. Therefore, it is necessary to introduce vegetation according to the water-repellency properties in the soil to maximize water conservation. However, further work on changes in the natural succession of abandoned agricultural soils related to plant species is necessary for better recognition of the processes related to soil hydrophobicity. This will allow better identification and prediction of SWR phenomena occurrence and improve management techniques for land, that could be affected by SWR. The inclusion of a greater number of sites with different plant species is required.

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Data availability The data presented in this study are available on request from the corresponding author.

Declarations

Ethics approval Not applicable.

Competing interests The authors declare they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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