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Leaf wettability and plant surface water storage for common wetland species of the Biebrza peatlands (northeast Poland)

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Abstract: Wetlands play a crucial role in buffering the effects of climate change. At the same time, they are one of the most endangered ecosystems on the globe. The knowledge of the water cycle and energy exchange is crucial for the practical preservation and exploiting their capabilities. Leaf wettability is an important parameter characterising the plant's ability to retain water on its surface, and is linked to the ecosystems' hydrological and ecological functioning. This research investigates the relationship between leaves' wettability based on contact angle measurements and water storage capacity (interception) for wetland vegetation. We performed the study for ten common plant species collected from Biebrza peatlands (Poland). We used CAM100 goniometer for the wetting contact angle measurements on the leaves' surface, and the weighing method for the plant surface water storage determination. The wetland plants' initial contact angle values ranged from 64.7° to 139.5° and 62.4° to 134.0° for the leaves' adaxial and abaxial parts, respectively. The average plant surface water storage was equal to 0.31 $g \cdot g^{-1}$, and values ranged from 0.09 to 0.76 $g \cdot g^{-1}$. The leaf hydrophobicity contributes to the amount of retained water. With increasing average contact angle, the amount of water retained on the plant decreased.

Keywords: Wetting contact angle; Interception; Peatlands; Biebrza wetlands.

INTRODUCTION

Nature-based Solutions (NbS) are crucial to mitigating climate change as, when done well, they support climate adaptation and resilience while protecting or restoring natural ecosystems (Sowińska-Świerkosz and García, 2022). NbS are estimated to provide 37% of the mitigation needed until 2030 to achieve the Paris Agreement targets (Díaz et al., 2019). Particularly wetlands, despite making up only 5–8% of the earth's surface, are the primary providers of ecosystem services, such as carbon sequestration, water retention, or acting as a sink for greenhouse gases (Mitch and Gosselink, 2007; Nahlik and Fennessy, 2016). Yet, despite their importance, wetlands have been degraded and disappearing at an alarming rate globally. Particularly threatened are the peatlands, which are highly sensitive to water level fluctuations, and water plays a crucial role in peat formation. They are, therefore, one of the most disappearing ecosystems in our climate zone; they are subject to progressive degradation due to changes in water conditions (Berezowski et al., 2018). Climate change further accelerates peatland degradation by altering water availability and precipitation variability, i.e. more frequent droughts, heavy rains and less snowy winters, and increased evapotranspiration (Dezsi et al., 2018; Marx et al., 2018). Nevertheless, wetland restoration can become a cost-effective method of climate change mitigation (Taillardat et al., 2020). However, its success depends on balancing future degradation and restoration (Zou et al., 2022).

Knowledge of the main processes and structure of the water cycle and energy exchange can support the preservation of wetland ecosystems and exploit their capabilities. For example, evapotranspiration, next to recharge, is an essential process of the hydrological cycle, which is still poorly recognised in wetlands. Even less is known about the role of vegetation in capturing water on their surface. Rainfall interception is a process of vegetated surfaces capturing and retaining water from precipitation. The rain that falls and reaches plant surfaces is temporarily retained on the plants' surface and then either evaporates into the atmosphere (interception loss) or makes its way to the ground by falling as drops (drip) or by flowing down branches and stems (stemflow). The interception on a single plant may be described as the canopy storage, i.e. the volume of water that can be retained. Grah and Wilson (1944) distinguished three components of canopy storage, i.e. transitory storage (water that would later drip off), conditional storage (water that could be dislodged by wind vibration of the plant) and residual storage (water that can only be removed by evaporation). Most studies estimating canopy storage measure the sum of conditional and residual (static) and exclude conditional storage (Dunkerley, 2000).

Except for water retention, interception has several other ecological implications. For example, a water droplet may hinder the

photosynthesis process on a leaf (Brewer and Smith, 1997) and contribute to pathogen development (Bradley et al., 2003). The amount of water retained on the leaf surface depends on its wettability and the plants' condition, species characteristics, air pollution or rainfall intensity (Jagels, 1994; Klamerus-Iwan, 2014; Klamerus-Iwan et al., 2018), making the rainfall-interception relations more complex. On a fine scale, interception is affected by droplet properties and leaf surface characteristics (Dorr et al., 2014).

One of the characteristic features of each leaf directly impacting water retention is its wettability. Whether water remains on the leaf's surface or is repelled depends on numerous leaf properties, including wax layer thickness (Barthlott and Neinhuis, 1997) and composition, trichomes (Ensikat et al., 2011; Koch et al., 2006; Muhammad et al., 2020) or the number and distribution of stomata (Xiong et al., 2018) and the leaf surface structure (Papierowska et al., 2019). Measuring the contact angle between a water droplet and the leaf surface can comprehensively describe a plant's ability to repel water from the leaf surface. Low angle values indicate high surface wettability, while high angle values indicate that water droplets form a spherical shape which more easily glides from the plant, making the plant non-wettable (Rosado and Holder, 2013). Plant leaves with lower wetting contact angles hold water droplets to their surface. As a result, the water droplet is relatively flat on leaves with a high wettability and evaporates more quickly than on leaves with low wettability (Pinon et al., 2006).

This research investigates the relationship between selected peatland plants' water storage capacity (interception) and their leaves' wettability, measured on both sides.

MATERIALS AND METHODS

Study area

We performed the field survey in the summer of 2016 in the homogeneous peatland habitat in Rogożynek, Poland (53°42'02.5"N 23°24'59.5"E) in the Upper Biebrza Basin (Fig. 1). Based on archival phytosociological surveys, dominant wetland species, typical for wet *Molinia* meadows were selected, which occurred in highest frequency in this area. In the part of the river valley near Rogożynek, we selected a study site of homogenous habitat. The plants selected for analysis were: *Carex rostrata* Michx., *Glyceria maxima* (Hartm.) Holmb., *Carex cespitosa* L., *Carex gracilis* Curtis, *Carex nigra* All, *Carex panicea* J. Carey, *Geum rivale* Ten, *Myosotis palustris* Hill., *Ranunculus repens* L., *Poa pratensis* L. Publications describing plant occurrence and zoning of plant communities in Biebrza Basin: (Oświt, 1991; Wassen et al., 2006) support the selection and the fact that the plants are characteristic of the most common habitats of Biebrza valley.

The Biebrza river valley is one of Poland's most significant and valuable wetland areas. It covers protected peatland habitats, including alkaline fens, raised bogs, transition mires, and quaking bogs arranged in a regular pattern of peat-forming plant communities (Wassen et al., 2003). The Upper Biebrza Basin is an approx. 40 km long section of the Biebrza valley, 1–3 km wide, where peat deposits can reach a thickness of up to 6 m. Groundwaters primarily feed the peatlands, while rainwater is a secondary water supply to a minimal extent (Wassen et al., 2003).

Typical fen peat soils that can be classified as Euthric Rheic Hemic Histosols occur in the research area (IUSS Working Group WRB, 2015). The thickness of the layer of sedge-reed peat exceeds 2 m. Soil bulk density in the upper layers of the profile (0–20 cm) ranges from 0.23 to 0.25 g cm^{-3}, ash content from 25 to 32%, and carbon content 26.4–27.9%. Deeper layers of peat (50–60 cm) have a lower bulk density (0.14 g cm^{-3}) and ash content (10%) as well as higher carbon content (47.6%) in comparison to the upper layers (Gnatowski et al., 2022).

The climate of the Biebrza river valley is temperate transitional, with evident continental influences. The mean annual air temperature (1991–2020) at the nearest (50 km) long-term meteorological station Suwałki is 7.6 °C, and the annual sum of precipitation is around 607 mm (Bartoszek et al., 2022). The coldest month at Suwałki station is January, with a mean air temperature of −3.9 °C and the warmest is July, with an air temperature of 18.2 °C (Górniak, 2021). The study year 2016 was very close to the climatological average with an air temperature of 7.7 °C and precipitation of 665.8 mm (this study, data from the Institute of Meteorology and Water Management, National Research Institute, IMGW-PIB). June 2016 (measurements period) was coldest than usual. The mean air temperature was about 15.1 °C (the climatological average for this month is 16.3 °C (Górniak, 2021). The monthly sum of precipitation in June 2016 was 63.1 mm, with a climatological average of 70.1 mm (Fortuniak and Pawlak, 2016). A week before measurements was rainless.



Fig. 1. Study site in the Upper Biebrza Valley.

Leaf contact angle measurements

We collected fresh, undamaged leaves of selected plant species in the field and transported the plant material immediately in a refrigerator to the laboratory for leaf surface wettability measurements. We used an optical goniometer CAM 100 (KSV Instruments, Finland) for contact angles (CA) were measurements according to the procedure described in Papierowska et al. (2018) within 1–2 days after sample collection. We repeated the procedure 15 times on a new sample for the leaves' adaxial (upper) and abaxial (bottom) parts. Due to the material's unavailability for *Carex cespitosa*, we performed the procedure only five times. CA measurements were performed consecutively at 1s intervals for 120 s on both sides of the drop (left and right). For further investigation, we calculated the average initial (CA_{ini}) values for the first (t = 1 s) and the average final (CA_{fin}) for the last measurements (t = 120 s), as well as the average from all measured values. The degree recognized for wettable surfaces is a contact angle of less than 90 degrees, whereas, for non-wettable surfaces, the contact angle is greater than 90 degrees. However, we also used a more detailed classification proposed by Aryal and Neuner (2010).

Plant surface water storage

We determined plant surface water storage similarly to Wohlfahrt et al. (2006). For every species, we collected approximately 60 samples of plant individuals were collected. We cut the individuals as close to the ground as possible and then submerged an end of a stem with hot wax to prevent wilting and to keep the material in a condition close to the natural state. In cases of species of significant size (e.g. tussock-forming sedges), we used part of the plant of approximately 100 g per sample). The procedure of measurements started with counting leaves and flowers, measuring the length and weight of a fresh plant. We used a scale with an accuracy of 0.01 g for the measurements (WPS2100/C, RADWAG). The last step of measurements was to fully submerge a plant in a 1.5 m long vessel filled with water to simulate rainfall. Between the first and the second weighting, we left the material for a few seconds to drip and then to be carefully weighted. After subtracting and averaging the mass of wet and fresh samples, we calculated the value of the amount of water intercepted on each species' surface (Suliga et al., 2015). We further used the difference between the weight of plants before (m_d [g]) and after (m_w [g]) water immersion to determine the plant mass storage capacity in [g_{H2O} / g]:

$$s = \frac{m_w - m_d}{m_d}$$

Statistical analysis

We performed a one-way analysis of variance (ANOVA) using Statgraphics plus (STSC Inc.–Statistical Graphics Corporation, 1996) to compare CA and mass storage values of different plant species. We transformed the data logarithmically to obtain a normal distribution of the variables. We used the mean Tukey's range test at $p < 0.05$ for mean comparison and regression analysis to study the relationship between variables.

RESULTS AND DISCUSSION

We present the average, and standard deviation of initial and final contact angle values obtained for all investigated species in Table 1. The adaxial leaf side of five species (i.e., *Carex cespitosa*, *Carex gracilis*, *Geum rivale*, *Myosotis palustris*, and *Ranunculus repens*) was characterized by the initial and final contact angles values smaller than 90 degrees and can be considered wettable. In turn, the remaining plants' leaves were non-wettable with contact angle values higher than 100 degrees (i.e. *Carex rostrata*, *Glyceria maxima*, *Carex nigra*, *Carex panicea*, *Poa pratensis*). We obtained the highest value of the initial contact angle equal to 139.5° for *Carex nigra*, for which the final contact angle was 131.2°. Furthermore, in this case, the contact angle values were stable throughout the measurement time of 2 minutes, as shown in Figure 1 (blue points). Abaxial leaf side analysis showed that in four cases (i.e. *Carex cespitosa*, *Carex gracilis*, *Carex nigra*, and *Carex panicea*), the initial and final contact angle values were higher than 90° and ranged from 111.6° to 133.7°. The measured initial contact angle values (adaxial part) for all considered species ranging from 64.7° to 139.5° were similar to those presented in the literature for wetlands plants. Measured contact angle values for coastal wetlands plants by Tellechea-Robles et al. (2020) ranged from 44.1° to 139.2°. In turn, Sikorska et al. (2017) obtained slightly higher contact angle values varying from 75° to 169° with air-dried plant leaves, in contrast to fresh leaves used in our study. According to the classification proposed by Aryal and Neuner (2010) and considering the

Table 1. Results of initial and final contact angle measurements in the adaxial and abaxial parts of the leaf with standard deviation. Different letters indicate significant differences among values after one-way ANOVA.

Species	CA_{ini} ± SD*	CA_{ini} ± SD*	CA_{fin} ± SD*	CA_{fin} ± SD*
	adaxial	abaxial	adaxial	abaxial
Carex cespitosa	64.7 ± 10.8 $^{a, b}$	122.7 ± 14.7 $^{d, e}$	57.5 ± 14.1 ^{b}	116.4 ± 12.3 ^{d}
Carex gracilis	79.8 ± 12.3 $^{c, d}$	134.0 ± 6.8 ^{e}	68.5 ± 16.2 $^{b, c}$	128.7 ± 6.7 ^{d}
Carex nigra	139.5 ± 13.3 ^{g}	133.7 ± 17.3 ^{e}	131.2 ± 9.7 ^{e}	124.0 ± 15.9 ^{d}
Carex panicea	121.0 ± 17.0 $^{e, f}$	114.3 ± 9.5 ^{d}	117.4 ± 15.6 $^{d, e}$	111.6 ± 9.6 ^{d}
Carex rostrata	132.6 ± 14.5 $^{f, g}$	62.7 ± 6.8 ^{a}	124.1 ± 11.5 ^{e}	49.8 ± 8.4 $^{a, b}$
Geum rivale	88.5 ± 10.1 ^{d}	88.4 ± 10.3 ^{c}	77.6 ± 14.2 ^{c}	81.8 ± 11.3 ^{c}
Glyceria maxima	107.1 ± 16.1 ^{e}	81.8 ± 5.5 ^{c}	101.6 ± 15.8 ^{d}	74.6 ± 8.0 ^{c}
Myosotis palustris	78.4 ± 17.8 $^{b, c}$	87.0 ± 10.8 ^{c}	67.1 ± 22.8 $^{b, c}$	80.4 ± 16.2 ^{c}
Poa pratensis	129.1 ± 18.6 $^{f, g}$	62.4 ± 10.0 ^{a}	125.1 ± 17.0 ^{e}	48.8 ± 12.7 ^{a}
Ranunculus repens	68.6 ± 15.0 ^{b}	74.7 ± 13.9 ^{b}	40.1 ± 14.0 ^{a}	59.1 ± 18.4 ^{b}

*SD – standard deviation

average contact angle for all 120 measurements on both parts of the leaves (adaxial and abaxial) from among ten analysed species, six were highly wettable, two were wettable and two non-wettable. The differences in leaf repellency between species may reflect selective strategies adopted for drought-prone environments or prolonged periods of precipitation (Rosado and Holder, 2013). Plants with hydrophobic leaves are more common in wetland environments though the degree of hydrophobicity can vary between species (Tellechea-Robles et al., 2020). By measuring the wettability of plant leaves, researchers can gain insights into the adaptive strategies of different wetland plant species and how they cope with inundation (Sikorska et al., 2017). This information can be helpful in wetland conservation and restoration efforts, as it can help identify plant species that are best suited to different hydrological regimes and promote the recovery of degraded wetland ecosystems. We noticed that in some cases (e.g., *Carex nigra*), the adaxial part of the leaf was less wettable than the abaxial part, and in other cases (e.g., *Ranunculus repens*) the reverse trend was observed (Fig. 2). Other studies showed that wettability differences also occur between the adaxial and abaxial sides of a leaf (Holder, 2012, 2007; Papierowska et al., 2018), which can result from physiological structure, e.g. stomata distribution (Xiong et al., 2018).

Determination of contact angles best characterizing the wettability of the leaves' surface poses a methodological challenge. Most of the authors show only one initial contact angle value, while we noticed that the behaviour of the water drop varies during the measurement time. In some species, the droplet placed on the leaf surface was stable over the time of the measurement or was subject to only minor spread (Fig. 2a), while in other cases, the droplet started to spread immediately, resulting in lower final contact angle values (Fig. 2b). Other authors also observed the contact angle changes over time in the case of materials of biological origin, e.g., wood (Rodríguez-Valverde et al., 2002) or plant leaves (Papierowska et al., 2020; Xu et al., 2010).

The leaf surface water storage we obtained for wetland plants ranged from 0.09 to 0.76 $g \cdot g^{-1}$ (average 0.31 $g \cdot g^{-1}$) (Fig. 3) and were lower than those presented in the literature for herbaceous species 0.12–1.26 $g \cdot g^{-1}$ (Xiong et al., 2019), and lower than obtained by Garcia-Estringana et al. (2010) for Mediterranean shrubs 0.23–2.26 $g \cdot g^{-1}$ (average 0.66 $g \cdot g^{-1}$). The measured and fitted relationships between the plant surface water storage and the average contact angle are presented in Fig. 4. We decided to present only data for the average angle of 120 seconds without separation of the adaxial and abaxial leaf sides due to weak correlations obtained for the separated data.

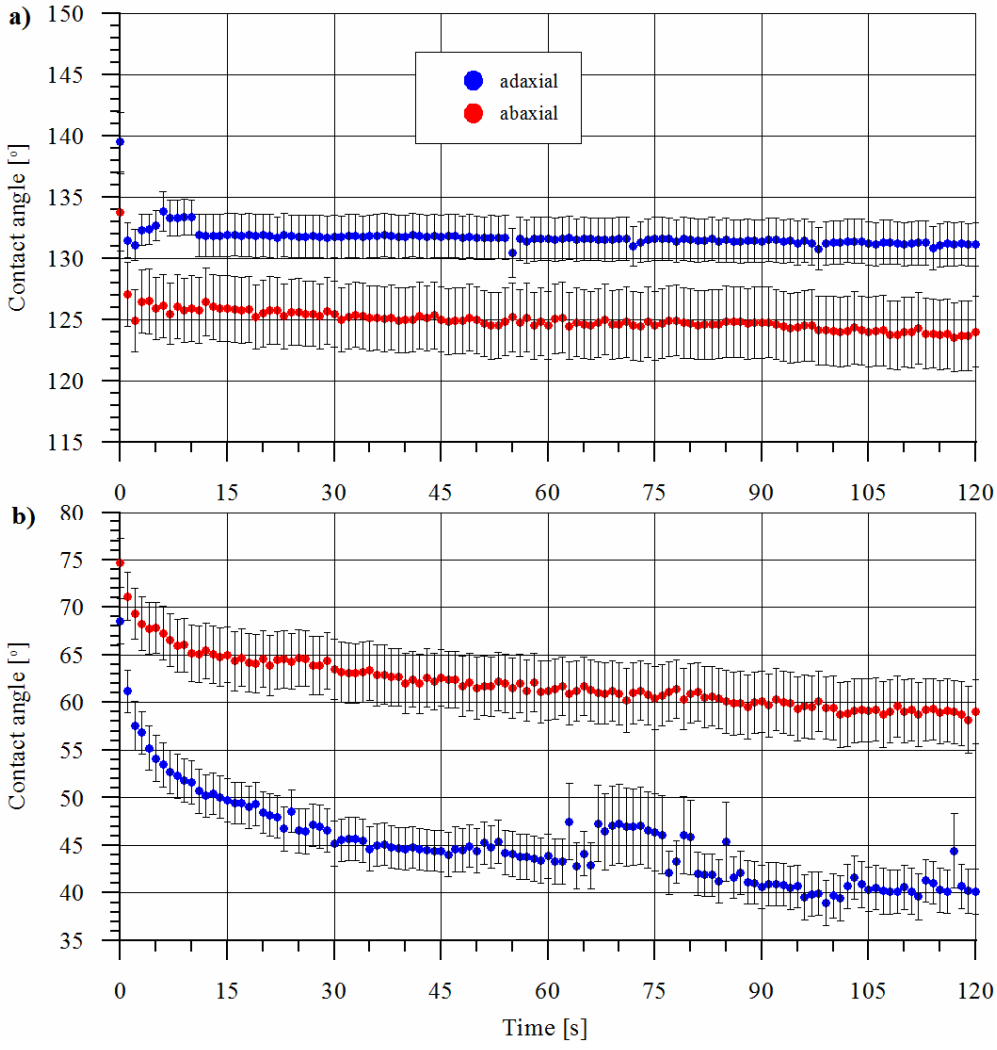


Fig. 2. Examples of contact angles measurement with standard error for *Carex nigra* (a) and *Ranunculus repens* (b).

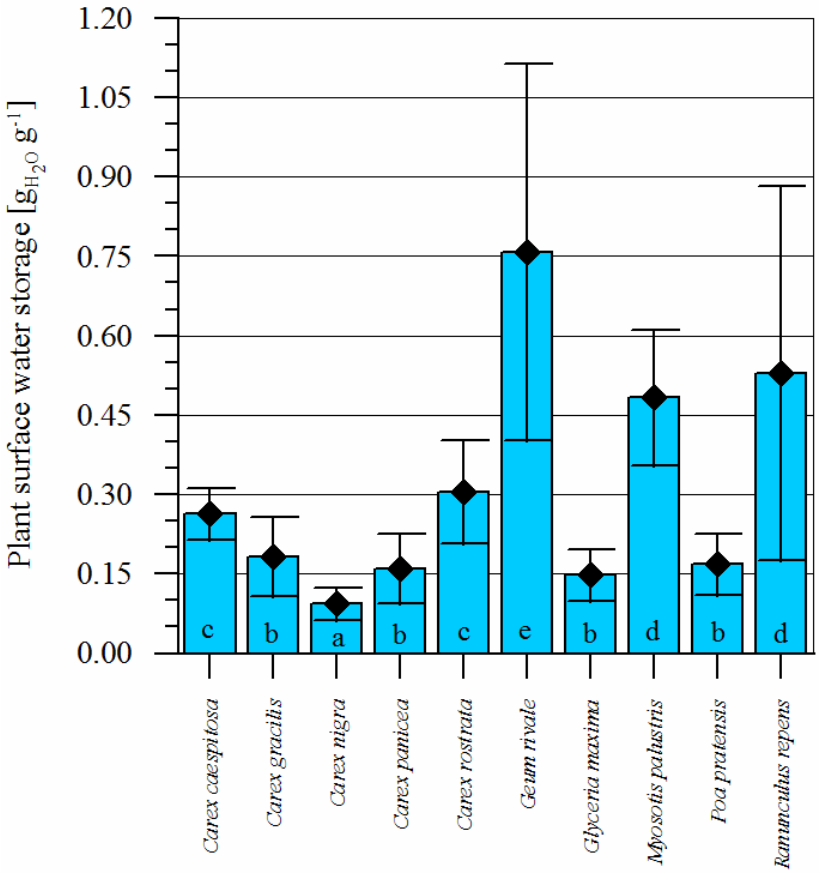


Fig. 3. Plant surface water storage with standard deviation for the examined plants. Different letters indicate significant differences ($p < 0.05$) among values after one-way ANOVA.

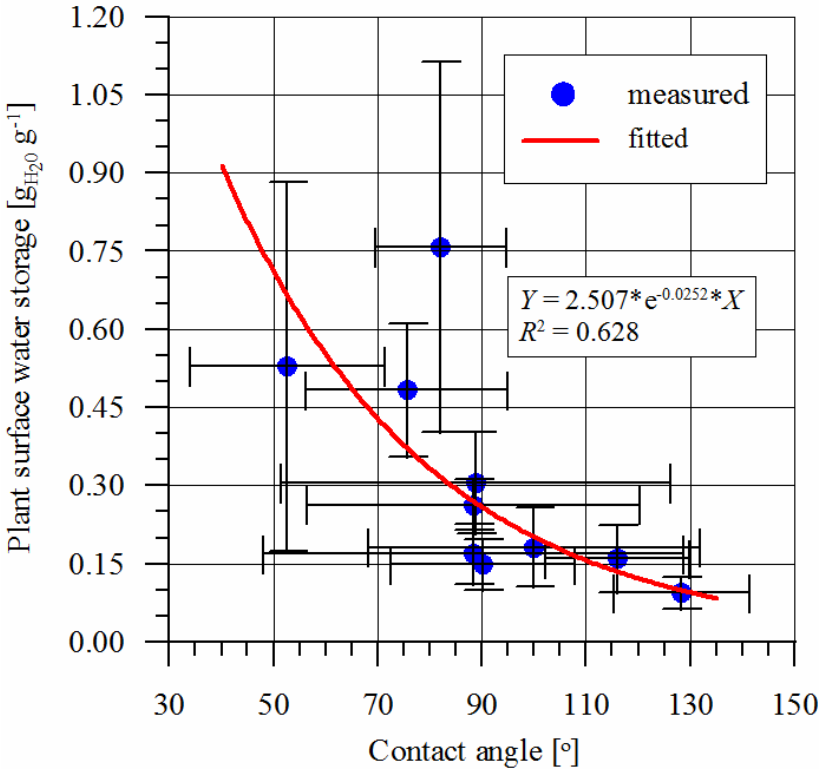


Fig. 4. The measured and fitted relationship between plant surface water storage and average contact angle. (error bars represent ± 1 standard deviation).

The leaf hydrophobicity contributes to the amount of retained water. With increasing average contact angle, the amount of water retained on the plant decreased. The determination coefficient (r^2) value was equal to 0.628. Our results agree with those of Xiong et al. (2018), who presented a negative linear relationship between plant surface water retention and leaf adaxial and abaxial contact angle. Holder (2013) obtained a similar tendency in his research. Among the many plant traits, wettability can be the best predictor of surface water retention at the plant level (Xiong et al., 2018).

Data on grassland vegetation's capacity to retain water on their surface are scarce in the literature. For comparison with other studies, we converted plant surface water storage expressed in (g_{H2O} g^{-1}) into area units by using fresh biomass measurement data formerly calculated for selected plant species in the Upper Biebrza Valley published by Suliga et al. (2015), report that fresh biomass values in June 2013 for *Carex caespitosa*, *Carex nigra*, *Carex rostrata* were 502, 300 and 238 g m^{-2}, respectively. Assuming that the species under consideration are dominant in the plant community and accepting the values of water surface storage coefficients we measured, the following interception values were obtained: for *Carex caespitosa* – 0.132 mm (0.132 L m^{-2}), *Carex nigra* – 0.028 mm and *Carex rostrata* – 0.073 mm. The calculated interception values are lower than those presented by Yu et al. (2012) for sub-alpine degraded grassland, which ranged from 0.217 to 0.612 mm, depending on the degree of habitat degradation.

Plant species typical for the rush plant communities that are regularly flooded are generally characterised by higher hydrophobicity and more repelling water from their surface, though the amount of water retained on their leaves varies from species to species. These plants are more likely to quickly get rid of the water retained on their surface. On the other hand, species typical for grasslands tend to accumulate a relatively large amount of water on their surface, as a hydrophilic surface favours water retention. Application of Nature-based Solutions for aquatic and wetland ecosystems frequently include designs where a critical component is an appropriate selection of plant species plantings. The designs suggest the use of rush species, known to be tolerant to large water fluctuations (Aevermann and Schmude, 2015; Pankratz et al., 2007).

Meanwhile, species associated with wet meadows adapted to retain relatively large amounts of water also perform well under changing water levels. Therefore, their use as admixtures alongside rushes for ecological restoration could enhance ecosystem services delivery related to water balance and reduction of runoff and positively boost biodiversity levels. Moreover, a higher proportion of these species in the composition could significantly increase the leaf retention capacity of plant surface water storage.

Our research contributes to the understanding of plant alterations of hydrological conditions within wetland ecosystems. By intercepting rainfall, plants change how the water reaches and affects the ground (Dunkerley, 2000). Furthermore, retaining water on the leaves alters the hydrological cycle by increasing evaporation and has a differential effect on the plant itself (Dawson and Goldsmith, 2018). At the same time, climate change affects not only the ecosystems functioning but also, indirectly, the altered ecosystems with changed vegetation composition, further contributing to changes in the hydrological cycle. Therefore, indicators of plants' water storage capacity can support estimating the far-reaching consequences of climate change induced water balance alterations. Our study suggests that, for instance, in fens, the plants would tend to hold water on their leaves, while the meadow species would hold less volume but for a more extended period, while rushes drain water the quickest.

The study indicates the importance of interception in wetlands, which are constantly being degraded by drainage, further intensifying climate change. Changes in temperature can affect the growth and phenology of wetland plants, which can in turn impact their interception capacity.

Wettability, being linked to the interception, has the potential to be used as a bioindicator for the degradation of wetland habitats and their restoration effects, and requires further investigation.

CONCLUSIONS

The wetland plants we analysed are characterised by variable wettability, with average initial contact angle values ranging from 64.7° to 139.5° (from highly wettable to highly non-wettable). These results confirm that there are different survival strategies among wetland plants originating from one habitat, even among species belonging to the same family (for instance, *Carex* genus, *Cyperaceae* family). Considered plants also revealed varying adaptations towards dealing with the surplus of water, which was visible in their varying water storage (0.09–0.76 $g \cdot g^{-1}$). We showed a strong linkage between leaf hydrophobicity and the amount of retained water. With increasing average contact angle, the amount of water retained on the plant decreased. Therefore, it can be assumed that water from precipitation flows more quickly on hydrophobic leaves, supplying soil moisture. The relation between wettability and interception allows using the wettability as a bioindicator of, e.g. wetland habitats restoration effects. The species-specific contact angles, however, require further research to exploit this potential, particularly in terms of the contact angle change over time. This knowledge will highly contribute to our understanding of precipitation-interception-infiltration processes and requires further investigation.

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