Variability of Water Repellency in Sandy Forest Soils under Broadleaves and Conifers in north-western Jutland/Denmark

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Abstract: Soil water repellency has important consequences for ecological and hydrological properties of soils and usually retards infiltration capacity and induces preferential flow. This phenomenon has been known to occur on a wide range of sites under a variety of climatic conditions. The objective of this study was to investigate and characterize soil water repellency on forest sites with identical substrate and climatic conditions, differing in tree age and species. In the Vester Torup Klitplantage, an area comprising a conifer dominated forest plantation stocking on sandy deposits in a coastal setting near the Jammer Bay in north-western Jutland/Denmark, four different forest plots were investigated for water repellency effects four times in 2005. To measure soil water repellency, the water drop penetration time test and the critical surface tension test were carried out. Both tests revealed a seasonal variability in water repellency, exhibiting the highest water repellency for the upper 10 cm of the soil during the summer months, whereas the variability between the different plots seems to be less significant. There was no coherence between humus forms, thickness of litter layer and water repellency.

Keywords: critical surface tension; Denmark; forest soils; hydrophobicity; water drop penetration time; water repellency

Water repellency, i.e. hydrophobicity of soils can severely impede infiltration; promote surface runoff and soil erosion (e.g. Doerr *et al.* 2000). It may also give rise to preferential flow of water and accelerated transport of chemicals into the groundwater (e.g. Hendrickx *et al.* 1993; Ritsema *et al.* 1993; Ritsema & Dekker 2000). Although originally described for semiarid (e.g. Schantz & Piemeisel 1917) and subtropical (Jamison 1947; Wander 1949) climatic conditions, it has become clear in recent years, that water repellency is more or less a global phenomenon (e.g. DeBano 1981; Wallis & Horne 1992; Doerr *et al.* 2000; Jaramillo *et al.* 2000). Incidences for non-mediterranean Europe have been described mainly from the Netherlands, e.g. for dune sands and pastures (e.g. Wessel 1988; Dekker & Ritsema 1994), further for organic soils under grass cover in Sweden (Berglund & Persson 1996), for soils under agricultural land use in Denmark (DeJonge *et al.* 1999) and Scotland (Hallett & Young 1999), and for moraine sand under horticultural land use in Lower Saxony/Germany (Bachmann 1988). Investigations of water repellency for soils with forest cover in central Europe are sparse and essentially restricted to afforested site consisting of mine dumpings (Katzur & Haubold-Rosar 1996; Biemelt 2001; Gerke *et al.* 2001). However, soil hydrological investigations carried out during the past years in the eastern part of Germany indicate that water repellency is a major concern also for forest sites on non-mining soils (e.g. Wahl *et al.* 2003, 2005; Bens *et al.* 2007).

In forest soils, water repellency depends on several variables, e.g. the wetting and drying history of the soil (Doerr & Thomas 2000), temperature (Dekker *et al.* 1998, 2001), content and type of soil organic matter (Doerr *et al.* 2005), thus by tree species respectively forest type (Doerr *et al.* 1998). The infiltration capacity of water repellent soils can be distinctly lower than those of wettable soils (e.g. Wang *et al.* 2000; Wahl *et al.* 2003, 2005) and consequently, surface runoff on water repellent soils is greater than on wettable soils (Burch *et al.* 1989; Crockford *et al.* 1991; Witter *et al.* 1991; Jungerius & ten Harkel 1994).

Degree and persistence of soil water repellency usually is reported to depend on soil water content (e.g. Dekker & Ritsema 1994; DeJonge *et al.* 1999). In general, the effect is stronger for dry soils and decreases with increasing soil moisture content. Differentiated investigations about the dependence of water repellency from water content yielded, however, conflicting evidence for different soils: For example, Witter *et al.* (1991) and Dekker and Ritsema (1994), amongst others, found very high intensities of water repellency for air-dry soil samples, whereas other authors report that the most pronounced water repellency was coinciding for water contents near wilting point (e.g. King 1981; De Jonge *et al.* 1999).

The objective of this study is to characterize the phenomenon of water repellency on sandy forest soils from the same geologic parent material on differently stocked forest plots in terms of seasonal variability and variability between plots and type of tree. In this context, two different measurement methods for water repellency were applied. Also, infiltration rates at saturation and near saturation were measured on the same plots. The effects of water repellency on infiltration will be treated separately in a forthcoming article.

MATERIAL AND METHODS

Experimental site

The study site Vester Torup Plantation (9°5’E, 57°7’N) is located approx. 20 km NW of the city of Fjerritslev in Northern Jutland in close vicinity to the coast of the Jammer Bay (Figure 1), characterizing the climate as temperate-oceanic. Throughfall and water soil chemistry is influenced by inputs of marine salt from the North Sea only 2 km distant. The total deposition of N in the area is approx. 9–11 kg N/ha/y (50% NH_4^+ and 50% NO_3^-) and the non-seasalt deposition of sulphur is approx. 4 kg S/ha/year (Ellerman *et al.* 2003).

In the study area, small hills created by salt tectonics were overridden by glaciers during the Weichsel Glaciation, leaving a discontinuous till capping. After postglacial (approx. 10 ka B.P.), the whole area was buried under aeolian sand of varying thickness, comprising the parent material of the soils (Table 1). The predominant soil types are Cambisols and Podsols, showing various signs of gleying. The water table is situated within the upper 1.5 m of the soil surface (plot A > 3 m).

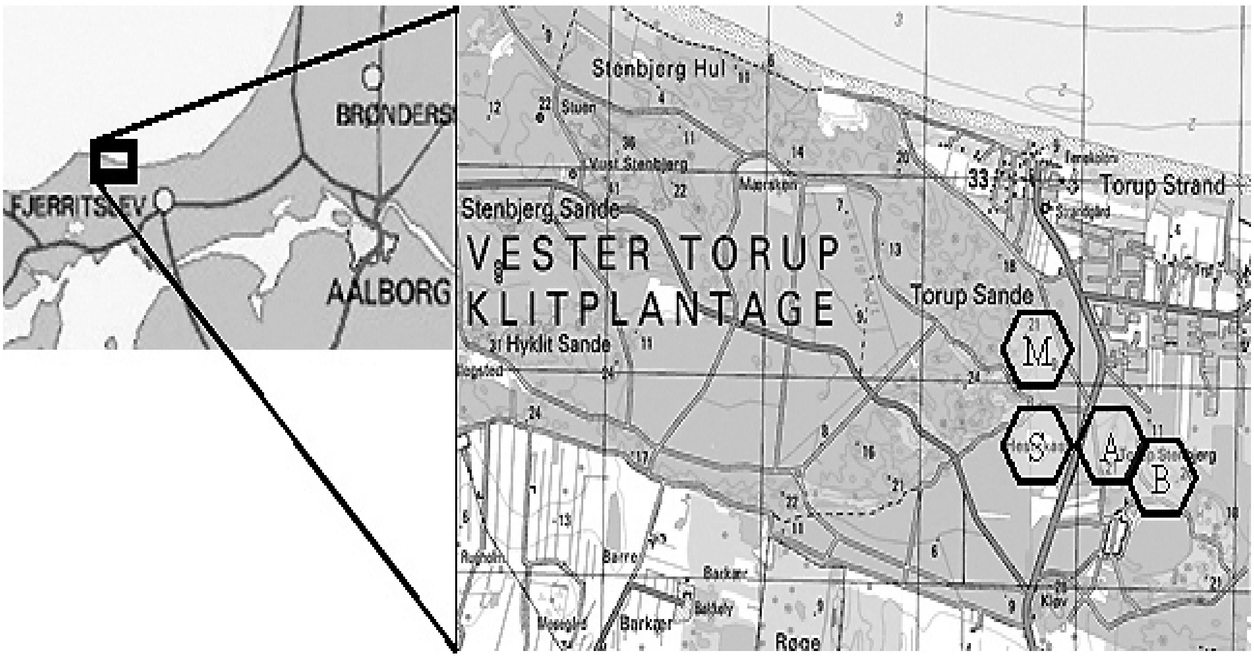

Figure 1. Location of the study site Vester Torup Plantage

Table 1. Physical characteristics of the study area

	Vester Torup plantation
Range of elevation of the study plots	3–15 m a.s.l.
Soil types	Cambisols and Podsols from aeolian sand
Coniferous species cover plantation	approx. 91% (2177 ha)
Mean annual precipitation	750 mm
Mean annual temperature	8°C
Potential evaporation	570 mm

The experiments were conducted on forest plots (denoted A, B, M, and S) dominated by *Abies alba* L. (plot A), *Fagus sylvatica* L. (plot B), *Pinus uncinata* Mill. ex Mirb. (plot M), and *Picea sitchensis* (Bongard) Carrière (plot S). The plots measured approx. 75 m by 75 m each. The plots are situated on flat ground (M and S), on a slope facing E (plot A) and at the hillfoot of that slope (plot B). The litter layer is mostly developed as moder, differing in thickness from one plot to the other. At plot M, the litter layer consists of a dense mat made up of roots from grasses, heather and litter material. Details about the plots are depicted in Table 2.

Soil sampling and sample preparation

Soil sampling for water repellency assessment was performed during four periods in 2005: January 2005, April 2005, July 2005 and November 2005. The repeat sample plots for each forest site were all located within an internal distance of approx. 5 m. During each sampling period, 5 undisturbed soil samples with a volume of 100 cm^3 were taken from just beneath the mineral soil surface on each forest site (approx. 0–5 cm and 5–10 cm depth), such that the total number of samples is 10 for each plot and each sampling date. Discarding some of the samples means that the number of water drop penetration time (WDPT) experiments varies among plots and dates (Table 3). In the laboratory the samples were oven-dried at approx. 45°C and a relative humidity of approx. 50% for three days. After the drying process, the WDPT tests and the critical surface tension (CST) tests were performed on the samples.

Assessment of water repellency

Two different types of tests were carried out in the present study: the WDPT and the CST test, because these methods are straightforward and relatively fast, and the results have a different and relatively well constrained physical significance: Whereas the WDPT test determines the persistence of water repellency, the CST test measures the apparent surface tension of the solid surface, i.e. the severity, or degree, of water repellence (Dekker & Ritsema 1994; Doerr *et al.* 2000). The WDPT test is originally described by Van't Woudt (1959). In the present study 5 droplets (approx. 40 µl each) were placed with a precision pipette on a smoothed soil surface and the infiltration time for each droplet was recorded. For further analysis, the median value (the median was chosen over the arithmetic mean, since it

Table 2. Details on the experimental plots used in the study (values given for 0–10 cm depth of the mineral soil; values in parentheses denote standard deviation)

Plot	Tree age (a)	Organic C content (%) $N = 10$	Sand (%) $N = 10$	Clay (%) $N = 10$	Humus form $N = 10$	Thickness of litter layer (cm)
A	74	5.0	94.1 (2.4)	2.5 (1.2)	Moder	6.8 (1.5)
B	75	3.1	93.2 (1.5)	2.6 (1.2)	Moder-mull/mull	4.8 (3)
M	53	4.3	93.5 (3.4)	1.7 (1)	Moder-grass type	9.7 (4.5)
S	73	2.8	95.2 (2.9)	1.2 (0.9)	Mor	13.6 (7.5)

is more robust in the presence of outlier values than is the mean) of those 5 records was used. Following Dekker and Jungerius (1990), 5 water repellency classes were distinguished: wettable (WDPT < 5 s), slightly repellent (WDPT 5–60 s), strongly repellent (WDPT 60–600 s), severely repellent (600–3600 s), and extremely repellent (WDPT > 3600 s). Recording was terminated after one hour (3600 s).

The CST is sometimes also referred to as ethanol percentage (Dekker & Ritsema 1994) or surface tension (Watson & Letey 1970) test. During this test, the surface tension of a liquid placed on a repellent material which is absorbed within a specific time, is termed the CST with low values for the CST giving a high degree of soil water repellency. The wetting angle α is a function of the three interfacial energies (σ, with unit N/m) liquid-vapour (σ_{lv}), solid-vapour (σ_{sv}), and solid-liquid (σ_{sl}) (Young 1805):

$$\sigma_{lv} \cos \alpha = \sigma_{sv} - \sigma_{sl} \quad (1)$$

If the contact angle α is greater than 90°, the soil is termed water repellent, for contact angles < 90°, it is wettable. According to (1), the wettability of a hydrophobic soil surface can be increased by lowering the surface tension of the liquid (σ_{lv}). With the ethanol percentage test, this is achieved by using different mixtures of water and ethanol. That means, the higher the concentration of ethanol in a liquid droplet which is absorbed within a specified time, the lower the liquid surface tension σ_{lv} and the higher the degree of water repellency. The surface tension of the resulting liquid depends exponentially on the volumetric ethanol content (vol. %; Roy & McGill 2002):

$$\sigma_{lv} = 0.06105 - 0.01475 \ln \left(\frac{\%\ \text{ethanol}}{5.8} + 0.5 \right) \quad (2)$$

Due to the use of a concentration (%) here, the constants in formula (2) differ from Roy & McGill's constants given for molarity.

The ethanol percentage (EP) test was carried out using 5 s as a drop penetration-time threshold (Dekker & Ritsema 1994) on samples, which were dried 3 days at 45°C. The ethanol concentrations used in the present study were 0 (71.3), 2 (63.2), 4 (58), 6 (54.2), 8 (51.2), 10 (48.6), 15 (43.8), 20 (40.1), 30 (34.7) and 40 (30.8) vol. % (in brackets: the corresponding liquid surface tensions (mN/m)).

Statistical analysis

One way ANOVA was used to test for significance of differences between means of CST and WDPT for different experimental forest plots and sampling/measurement periods, applying the program SPSS (version 15.0.0.1). Prior to statistical analysis data were tested for normality by applying the PP-test. Comparisons between single means were done by using Fischer's least significant difference when the F value in the ANOVA was significant. The null hypothesis was rejected at customs level ($P = 0.05$). For the analysis, the data were pooled according to the four experimental plots and four sampling periods exploited in the present study.

RESULTS AND DISCUSSION

For oven-dried conditions, the overall proportion of extremely repellent samples is very high for all plots (Figure 2). The highest proportion of extremely repellent samples is observed at the plot S (stocked with *Picea sitchensis*), while the other three stands exhibit slightly lower proportions of extremely water repellency. Furthermore, virtually no plots with wettable conditions are found and only a very small proportion of slightly water repellent conditions (less than 1.5%). The classes of strong water repellency and stronger are holding a share of > 98.5% of all values for the four plots.

Contrasting the rather small inter-stand differences are the differences between the sampling dates, being decisively higher. Especially the late spring and summer samples exhibit a much higher share of extremely water repellent samples, being

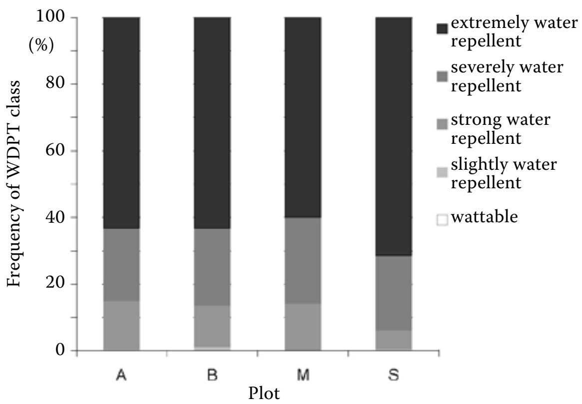

Figure 2. Frequency of water drop penetration time (WDPT) classes at 0–10 cm depth for the four experimental plots (oven-dried samples)

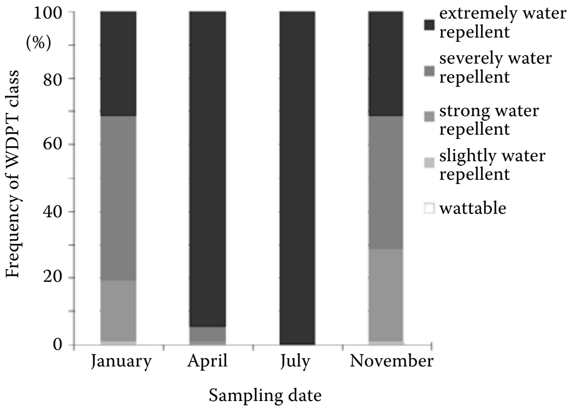

Figure 3. Frequency of water drop penetration time (WDPT) classes at 0–10 cm depth for the four experimental plots for the different sampling dates (oven-dried samples)

much higher than the proportions of the early spring and also late autumn samples (Figure 3). There seems to be a marked seasonal trend, with extreme water repellency lasting throughout late spring and until early autumn. Whereas differences in WDPT values for field moist samples may be attributed to the differing water content (Wahl *et al.* 2005), this cannot be the case for oven-dried samples. Because of the standardized test conditions for the assessment of the persistence of potential water repellency, the temporal differences cannot be explained by differences in water content or ambient temperature. These differences are thought of being caused either by the amount of water content prior to drying (the drying/wetting cycles, i.e., the drying/wetting history of the material prior to sampling, e.g. Doerr and Thomas (2000)), or the quality and type of litter material, including state of transformation, or a combination of both. Differences may be triggered by changes in the chemical composition or reactivity of the organic matter during the drying cycle. As organic matter contents were not recorded for each sampling date and plot, this explanation might be somewhat biased, on the other hand, it is a known fact that humus stock and organic matter content varies throughout the year with the highest amount of both solid and dissolved organic matter are reported for summer and autumn compared to winter and spring conditions (e.g. Kaiser *et al.* 2001).

CST values indicate a high share of samples with repellent attributes both for the plots (Figure 4) as for the different sampling periods (Figure 5). Practically, there are no samples which could be characterised as exhibiting wettable conditions, when samples with a CST of < 65 mN/m are thought of being repellent or 'somewhat repellent' (e.g. Scott 2000). King (1981) and Doerr (1998) also provide repellency ratings. The rating of Doerr (1998) is based on findings from sandy-loamy soils from Northern Portugal applying the following classes: 7, extremely hydrophobic (36% EP); 6, very strongly hydrophobic (18.5% EP); 5, strongly hydrophobic (13% EP); 4, moderately hydrophobic (8.5% EP); 3, slightly hydrophobic (5% EP); 2, hydrophilic (3% EP); and 1, very hydrophilic (1% EP). Applying Doerr's (1998) rating to this study would result in characterising the samples used in the present study as belonging to the hydrophobicity classes 6 and 7. This is roughly in line with the findings from the WDPT experiments (Figures 2 and 3).

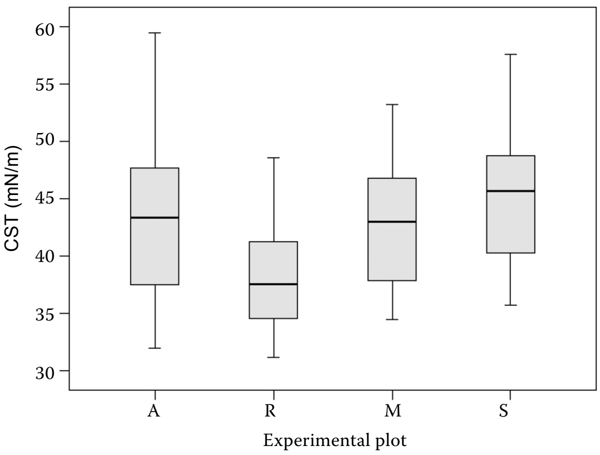

Figure 4. Boxplots of critical surface tension (CST) values for the experimental plots (0–10 cm depth); the boxes denote the 25 and 75 percentile split by the median, while the whiskers denote the minimum and maximum

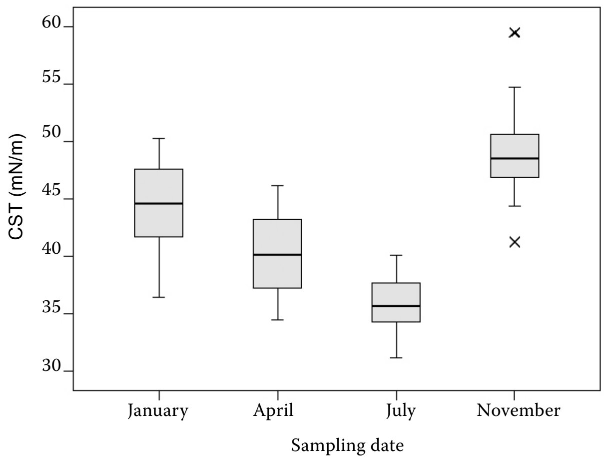

Figure 5. Boxplots of critical surface tension (CST) values for the different sampling dates (0–10 cm depth); outliers are indicated as crosses

Table 3. Number of water drop penetration time (WDPT) measurements for the four experimental plots and the different sampling dates for dried (potential WDPT) samples

Plot	January		April		July		November		Sum		
	depth (cm)										
	0–5	5–10	0–5	5–10	0–5	5–10	0–5	5–10	0–5	5–10	0–10
A	29	31	25	30	31	31	31	29	116	121	237
B	30	26	24	20	29	38	25	30	108	114	222
M	28	20	31	37	25	29	31	20	115	106	221
S	26	25	30	21	21	32	18	21	95	99	194
Sum	113	102	110	108	106	130	105	100	434	440	874

On an overall basis, the statistical significant evidence regarding the differences between sample plots is only detected for some of the forest plots, resulting from a small number of samples, and sampling dates (Tables 4 and 5), despite the trends depicted from Figures 4 and 5. For the plots, the differences in means are only significant for plot A compared to B and S, while it is not significant for plot M. For the sampling dates, there are significant differences between July and January, April and November, with the July dates exhibiting significantly lower CST values (i.e., higher repellency) compared to the other sampling dates. This is especially evident for the comparison July vs. November. These overall figures are in line with the variability within the dates/plots (intra date and plot variability) being somewhat higher than the variability between the dates/plots (inter date and plot variability) (Table 4).

In the present study, the plot with the highest degree of soil water repellency in terms of CST

Table 4. Summary statistics of critical surface tension (CST) values (mN/m) for the four experimental plots and the different sampling dates (SD – standard deviation, *CV* – coefficient of variation)

	Mean	Median	*CV* (%)	N	SD
Plot A	43.45	43.86	14.96	36	6.5
B	38.86	37.65	12.61	35	4.9
M	43.18	43.20	13.43	35	5.8
S	45.01	45.65	11.33	34	5.1
January	44.75	45.34	8.04	37	3.6
April	40.34	40.16	8.92	32	3.6
July	36.27	36.42	6.89	37	2.5
November	49.42	48.75	8.30	34	4.1

values (plot B) does not coincide with the plot exhibiting the highest proportion of extremely water repellent samples, which is plot S (Figure 2). Likewise, plot B and M exhibit the smallest proportion of samples with wettable conditions. The differences between the findings from the WDPT and CST tests might be due to the different physical significance of both tests. Several authors report of only incomplete correlations between the two tests, differing both seasonally and with soil depth. Doerr (1998) reports an overall value of $r = 0.73$ for a sandy-loamy soil from Portugal, while Scott (2000) reports a correlation of $r = -0.88$ for South African soils. Other, more qualitative descriptions, are given e.g. by Dekker and Ritsema (1994), reporting a 'no good correlation', while Harper and Gilkes (1994) found a 'good' correlation. Crockford *et al.* (1991) found for sandy clay-loam soils with eucalypt vegetation 'a reasonable correlation between aqueous ethanol concentrations and WDPT for most but not all sites'. For this study it must be noted that the difference of CST means for plot B is the only one being statistically significant (Table 4). Focussing on the differences between sampling dates results in a somewhat other picture giving a largely correlated trend between WDPT and CST, with highest repellence during the summer months and the lowest during late autumn (Figure 2 and Table 3).

The data presented in this study reveal mostly extremely water repellency, being much higher than those found in other studies (e.g. Richardson & Hole 1978; Huffmann *et al.* 2001) and furthermore being more similar to results reported from warm-dry Mediteranean–type climate rather than temperate-humid climate (e.g. Crockford *et al.* 1991; Doerr *et al.* 1996).

Table 5. *F*-values matrix for means testing (significant differences marked * = 0.1; ** ≤ 0.05; *** ≤ 0.01; n.s. = not significant)

	A	B	M	S	January	April	July	November
Plot A	–	**	n.s.	*				
B		–	n.s.	n.s.				
M			–	n.s.				
S				–				
January					–	n.s.	**	n.s.
April						–	**	n.s.
July							–	***
November								–

Soil water repellency was found to exhibit a pronounced seasonal variability. The highest values of soil water repellency were found during the summer months, and the lowest during the late autumn, and early winter months. As this finding is based on values determined from oven-died samples, different soil water contents or temperatures should have had no influence on the WDPT and CST values. Rather, the amount, type, and quality of the soil organic matter, varying throughout the year, exerts probably the predominating influence upon the seasonal variation of water repellency, as seasonal variations have been reported from other forest sites in temperate-humid regions (e.g. McDowell & Likens 1988; Kaiser *et al.* 2001). These findings are also reported from forests situated in a more continental dry climate (e.g. Fischer *et al.* 2002; Bens *et al.* 2007). Furthermore, the seasonal variation might be influenced by the wetting and drying history of the samples prior to sampling and experiments (Doerr *et al.* 1998) as well as temperature (e.g. Dekker *et al.* 1998; Doerr & Thomas 2000).

Applying two different tests for characterising water repellency resulted in qualitatively similar data, although some differences were found. It has been found that the two methods obviously convey a different physical message about water repellency, which was also noted by Dekker and Ritsema (1994). Contrastingly, some authors refer to just one method, preferring the CST test as only water repellency test. Scott (2000) and Huffmann *et al.* (2001) reject the WDPT test being time consuming and producing strongly bimodal and non-normal results. On the other hand, other authors apply only the WDPT test (e.g. Jex *et al.* 1985; Chan 1992). It should be borne in mind, that the two methods applied here are intrinsically not able to differentiate between soil surfaces with contact angles < 90° (Letey *et al.* 2000). However, also contact angles < 90° on soil surfaces can have significant impact upon soil-water relationships, e.g. when infiltration is looked upon (e.g. Wahl *et al.* 2003, 2005).

Although this study made use of four different tree species, stocking on more or less identical geologic substrate, the statistical significant differences between the different plots were only few. However, it was found that the plot B, stocked with *Fagus sylvatica*, exhibited the most pronounced water repellency effects throughout the year. Other studies (e.g. Scott & van Wyk 1990; Crockford *et al.* 1991) have shown a correlation between water repellency and litter quality, implying higher water repellency on sites with 'ecologically less favorable' humus forms (e.g. moder and mor-like forms), in this case represented by the plots M and S. Higher water repellency under mor-type humus forms compared to other humus forms are also reported by Sevink *et al.* (1989) and Imeson *et al.* (1992). Ziegler and Zech (1989) and Dinel *et al.* (1990) report the concentration of hydrophobic lipid compounds to decrease with increasing efficiency of decomposition. Contrary to this, Bachmann (1996) found for soils on glaciofluvial and aeolian sediments under forest-land use in Lower Saxony/Germany a positive correlation between the degree of humification and the contact angle, giving increasing water repellency with increasing humification. Likewise, Wahl *et al.* (2005) report higher water repellency (CST test) on plots stocked with European beech compared to plots stocked with Scots pine from northeast Germany.

CONCLUSION

Summarizing, the results presented here indicate that soil sampling at specific dates within a year are not capable of tracing the hydrophobic soil properties because of the seasonal variability. This could be partly solved be applying semi-automatic samplers for soil water in different depths on the different plots and analysing for the concentration of hydrophobic lipids and esters in the leachate. Furthermore, on the basis of this study' findings, it does not seem to be justified to characterize certain humus forms for problem inducing with respect to water repellency, as differences in water repellency related to forest and canopy structure are also obtained for the other sampling periods. This study reveals no clear correlation, if there is one at all, between humus form/thickness of the litter layer, and the persistency/strength of water repellency. This might at least partly owe to the variation in production of water repellent substances over time and space from different types of litter, resulting in variations of the free surface energy of amphiphilic and water repellent compounds and their internal variation of distribution. Further studies will have to verify to what extent the results of this study also apply outside the local conditions described here, and to which extent the results for the different tree species in the present study may be characteristic or site specific.

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