Effects of surfactant treatments on the wettability of a water repellent grass-covered dune sand

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Abstract. The objective of this study was to evaluate the effectiveness of the surfactant formulation Primer®604 for amelioration and management of soil water repellency in grass-covered dune sand. The soil is severely to extremely water repellent to a depth of >0.50 m during dry periods. Primer®604 was applied 12 times between 22 April and 23 November 1999. During that period, soil samples were taken in the untreated and treated plot—8 times in transects and 2 times in soil blocks. A total of 4950 samples were collected for assessment of the actual water repellency and for the spatial and temporal variability of the water content of the soil. Resistance to wetting was determined by measuring the wetting rate of field-moist samples. Measurements of water repellency revealed that applications of Primer®604 resulted in less persistent water repellency in the surface layer to a depth of 0.05 m. No effects were observed deeper in the soil profile, likely due to adsorption of the surfactant material in the surface layer. In the surface layer (0–0.025 and 0.025–0.05 m), the critical soil water content below which the soil is actually water repellent in the field was lowered distinctly by the application of Primer®604, potentially due to coating of water repellent particle surfaces by the surfactant. This suggests that the surface layer (0–0.05 m) in the Primer®604-treated soil can dry to lower water contents than in the untreated soil before water repellency is induced. The thatch layer (0–0.025 m) of the treated soil was often found to have slightly higher water contents than of the untreated soil. The surfactant did not equalise the uneven moisture distribution in the soil below the surface layer (0–0.05 m). Primer®604 applications increased the wetting rate of field-moist samples from the thatch layer. This may result in a more effective wetting of the root-zone during rain events or irrigation, and a reduction in runoff.

Additional keywords: actual water repellency; critical soil water content; irregular wetting; preferential flow; water drop penetration time (WDPT) test; wetting rate.

Introduction

The phenomenon of soil water repellency has been recognized in various parts of the world (DeBano 2000; Doerr et al. 2000; Jaramillo et al. 2000) including the Netherlands (Hooghoudt 1950; Dekker and Jungerius 1990; Dekker and Ritsema 1996, 2000) and has resulted in serious land-use problems in agriculture (Blackwell 2000) and an ongoing management problem on sand-based turfgrass systems (Cisar et al. 2000).

It has been recognized for many years that soil water repellency is often a function of the type of organic matter incorporated in the soil, and that certain types of organic matter cause water repellency by several means (e.g. Doerr et al. 2000; Dekker et al. 2001; Hallett et al. 2001).

Soil water repellency may dramatically affect field-scale water and solute movement, and has often been underestimated (Bauters et al. 2000). Water repellency and its spatial variability have been shown to cause non-uniform wetting and preferential flow in many soils (Dekker and Ritsema 1994, 1996, 2000; Ritsema and Dekker 1996; Ritsema et al. 1998b).

Based on experimental observations, Ritsema et al. (1993) proposed a conceptual model for water flow in water repellent sandy soils. According to this model, the initially uniform water infiltration is disrupted within the first few centimeters of the water repellent soil, causing water to move laterally towards microdepressions and regions with lower water repellency, where fingers are formed. Water is transported along these preferential flow pathways until decreasing water repellency in the soil at increasing depth causes divergence of the flow lines (Ritsema et al. 1998a; Nguyen et al. 1999). This process, occurring at the onset of an infiltration or leaching event, may drastically affect subsequent water movement (Ritsema and Dekker 1995).
Soil surfactants have been developed as a possible means for overcoming the problems caused by water repellent soils (Moore 1981; Rieke 1981; Kostka et al. 1997; Dekker et al. 2000; Kostka 2000). Wetting agents that have a strong affinity for the surface of hydrophobic soil particles and adsorb strongly at the soil surface will enhance infiltration rates at the soil surface interface. On the other hand, good water dispersion throughout the profile would require uniformity of penetration of the wetting agent in the profile. It is clear that a true test of the effectiveness of a soil wetting agent must include the assessment of the uniformity of distribution of the water in the soil, as well as the increase in infiltration rate and water content. The objective of our study was to evaluate the effectiveness of Primér®604 for amelioration and management of soil water repellency in a pasture on a native dunegrass. The present paper describes the influence of the surfactant in reducing the severity of soil water repellency and increasing the wetting rate, and its effect on the spatial variability in soil water content, water flow, and wetting patterns.

Materials and methods

Field-soil and treatment

The wetting agent was applied to a plot (25 by 5 m) of a dunegrass with a grass cover near Ouddorp in the southwestern part of the Netherlands. An untreated adjacent plot was used for comparison. The wetting agent was applied to a plot (25 by 5 m) of a dune sand, soil blocks (0.25 by 0.75 by 0.19 m) were sampled in vertical transects by intensive sampling of the treated and the untreated plots. To allow more detailed determination of the wetting patterns in the dunegrass, soil blocks (0.25 by 0.75 by 0.19 m) were sampled in both plots on 25 October and 23 November 1999 (Dekker et al. 2000). The soil of the transects and blocks was sampled at 6 depths (0–0.025, 0.025–0.05, 0.05–0.075, 0.075–0.12, 0.12–0.165, and 0.165–0.3 m), using steel cylinders with a diameter of 50 mm. In each transect and at each depth, 35 adjacent samples were taken over a distance of approximately 1.8 m. A total of 3150 samples were collected in the period 22 April–23 November 1999.

Soil sampling

Between 22 April and 12 October 1999, the spatial and temporal variability of the volumetric soil water content was evaluated 8 times in vertical transects by intensive sampling of the treated and the untreated plots. To allow more detailed determination of the wetting patterns in the dunegrass, soil blocks (0.25 by 0.75 by 0.19 m) were sampled in both plots on 25 October and 23 November 1999 (Dekker et al. 2000). The soil of the transects and blocks was sampled at 6 depths (0–0.025, 0.025–0.05, 0.05–0.075, 0.075–0.12, 0.12–0.165, and 0.165–0.3 m), using steel cylinders with a diameter of 50 mm. In each transect and at each depth, 35 adjacent samples were taken over a distance of approximately 1.8 m. A total of 3150 samples were collected in the transects. In each of the 4 soil blocks, 75 samples were taken at each depth along a horizontal plane in a regular grid of 15 by 5 samples. A total of 1800 samples were collected from all blocks. The cylinders were pressed vertically into the soil, emptied into plastic bags, and re-used. Plastic bags were tightly sealed to minimize evaporation. The field-moist bagged soil was weighed. ‘Actual’ soil water repellency was measured (Dekker and Ritsema 1994), and after drying in a fan oven during 1 week at 25°C, ‘potential’ water repellency was measured. Samples were further dried at 105°C and weighed again to calculate the water content and dry bulk density of each sample. A total of 4950 samples were collected and measured in this way.

Water Drop Penetration Time (WDPT) test

The persistence or stability of water repellency of the soil samples was examined using the WDPT test (e.g. King 1981). Using a standard medicine dropper, 3 drops of distilled water were placed on the smoothed surface of a soil sample, and the time that elapsed until the drops infiltrated was determined. Soil water repellency of all 4950 samples was measured under controlled conditions at a constant temperature of 20°C and a relative air humidity of 50%. In general, a soil is considered to be water repellent if WDPT exceeds 5 s (Dekker 1998). We applied an index allowing a quantitative classification of the persistence of soil water repellency as described by Dekker and Jeungerius (1990). Thus, 7 classes of repellency were distinguished, based on the time for water drops to infiltrate the soil: class 0, wettable, non-water repellent (infiltration within 5 s); class 1, slightly water repellent (5–60 s); class 2, strongly water repellent (60–600 s); class 3, severely water repellent (600 s–1 h); and extremely water repellent (> 1 h), further subdivided into class 4 (1–3 h), class 5 (3–6 h), and class 6 (>6 h).

Water repellency was measured on the field-moist samples (‘actual’ water repellency), and again after drying at 25°C. The severity of water repellency measured on dried soil samples, the so-called ‘potential’ water repellency, is considered to be the most appropriate parameter for comparing soils with respect to their sensitivity to water repellency (Dekker and Ritsema 1994), because differences in water content are wiped out. We measured the ‘actual’ water repellency on the field-moist samples immediately after recording their wet weight. By measuring the water content of the samples, we could assess ‘corrected soil water contents’ for the different depths of the intensively sampled transects and soil blocks. The soil is wettable above, and water repellent below, these values (Dekker and Ritsema 1994).

Wetting rate measurements

Resistance to wetting was determined several times by measuring the wetting rate of field-moist samples collected at depths of 0–0.025 m in the treated and untreated plots prior to surfactant application. The samples were collected in steel cylinders (18 cm) with a height of 25 mm and a diameter of about 30 mm. To measure wetting rate, three samples, within their steel cylinders, were subjected to a constant pressure head of ~2.5 cm water applied at the bottom of the samples (Dekker et al. 1998). The experimental set-up was designed in such a way that water content changes at 1.0 vol% increments were recorded automatically. All measurements were performed in a controlled environment laboratory with a constant temperature of 20°C and a relative humidity of 50%.

Results

Actual water repellency

The entire soil profile was wet at the beginning of the study on 22 April 1999. All 210 samples taken at depths between 0 and 0.19 m were wettable or non-water repellent, exhibiting WDPT values <5 s.

In the period that followed, the field-soil became drier, and as a consequence, all samples taken on 17 May at depths between 0 and 0.165 m and the majority of the samples at
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depths of 0.165–0.19 m were water repellent (Figs 1 and 2). The repellency of the thatch layer at depths of 0–0.25 m ranged between 60–600 s and 1–3 h (Fig. 1). The severity of actual water repellency in the soil profile increased with depth towards 0.12 m. At depths of 0.05–0.12 m nearly 65% of the samples from the untreated and treated plots had WDPT values >6 h on 17 May 1999 (Fig. 2). A decrease in severity of actual water repellency occurred in the soil layers sampled below 0.12 m on almost all sampling dates (Fig. 2).

The variability in actual water repellency was high in the soil over short distances at all depths in the untreated and treated plots, with WDPT values often varying between <5 s and >6 h on all sampling days (Figs 1, 2). Relatively small differences in actual water repellency between the untreated and treated plot were determined for samples collected at depths of 0.07 to 0.19 m (Fig. 2). The thatch layer (0–0.025 m depth) was found to be wettable for both plots on 22 April, 12 August, 12 and 25 October, and 23 November 1999. More wettable samples were recorded at depths of 0–0.025 m and 0.025–0.05 m for the Primer®604-treated plot compared with the untreated plot on 1 June and 8 July 1999 (Fig. 1). Distinctly lower WDPT values were recorded for the samples taken in the thatch layer and in the surface layer at depths of 0.025–0.05 m in the treated plot compared with the untreated plot on 2 and 21 September 1999 (Fig. 1).

The spatial and the temporal variability of the persistence of actual water repellency in transects of the untreated and treated plot were remarkable (Fig. 2). Within a horizontal distance of only 1.8 m, extreme water repellency was detected in dry soil areas, and wettable soil in preferential

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**Fig. 1.** Relative frequency of the persistence of actual water repellency of field-moist samples taken at depths of 0–0.025 and 0.025–0.05 m in the untreated and treated dune sand on 9 sampling days (n = 35 at both depths for the 17 May to 12 October 1999 transects, and n = 75 for the 25 October and 23 November 1999 soil blocks).
Fig. 2. Relative frequency of the persistence of actual water repellency of field-moist samples (n = 35) taken at 4 depths (top to bottom: 0.07–0.095, 0.095–0.12, 0.14–0.165, 0.165–0.19 m) in the untreated and treated dune sand on 7 sampling days.
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Spatial variability in severity of actual water repellency is demonstrated by the contour plots of the 25 October 1999 soil blocks, with a size of only 0.75 by 0.25 by 0.19 m, or 0.036 m$^3$ (Fig. 3). It is worthy of note that the actual water repellency at depths of 0.0825–0.1775 m in the treated plot was more severe and distributed over larger areas than in the untreated plot. We assume that the applications of Primer® 604 resulted in a movement of the surfactant from the thatch layer into the preferential flow paths and thereby induced an enhancement of wetting of these flow paths. As a consequence, dry pockets in the treated soil were provided with less rainwater and were therefore more persistent than in the untreated soil. Although the severity of actual water repellency decreased during the autumn rains, extreme repellency with WDPT values > 1 h still occurred in dry soil pockets of the soil block of 23 November 1999 (not shown here).

In conclusion, the application of Primer® 604 resulted in a decrease in water repellency in the surface layer to a depth of 0.05 m, due to adsorption of the surfactant in this zone. Deeper in the profile no positive effects could be observed.

**Fig. 3.** Contours of the persistence of actual water repellency in horizontal planes (0.25 by 0.75 m) at 6 depths in the untreated and treated 25 October 1999 soil blocks.
Fig. 4. Minimum (−), mean (○), and maximum (−) soil water contents of samples taken at 6 depths in the 8 transects (n = 35) and 2 soil blocks (n = 75) of the untreated and treated dune sand between 17 May and 23 November 1999.
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**Soil water content**

A high degree of spatial and temporal variability of the soil water content was often found in all layers sampled (Fig. 4). The highest water contents were found in the surface layers, which possessed higher organic matter contents and lower dry bulk densities than the deeper layers. Relatively high soil water contents were established at depths between 0 and 0.05 m in April (not shown), October, and November; however, spatial variability remained high. For instance, the soil water content at depths of 0–0.025 m varied between 31.4 and 69.3 vol%, and at depths of 0.025–0.05 m between 26.1 and 57.5 vol% at the start of the experiment, on 22 April 1999. At the end of the experiment, on 23 November 1999, the soil water content of the thatch layer in the untreated plot varied between 29.9 and 47.5 vol% and in the treated plot between 33.7 and 54.3 vol% (Fig. 4).

The mean soil water content in the thatch layer was often slightly higher in the treated plot than the untreated plot (Fig. 5). For example, in the treated plot, the mean soil water content was 43.8 vol% at depths of 0–0.025 m on 25 October 1999, compared with 40.8 vol% in the untreated plot. The plot treated with Primer®604 applications exhibited slightly higher mean soil water contents at all depths and in most transects compared with the untreated plot (Fig. 5). The diagrams of these transects also show clearly the wide variability which often existed between the soil water contents in the surface layer and in the soil at depths of 0.095–0.19 m.

Relatively dry transects, with small variations in water content, were sampled on 17 May and 2 September 1999 (Fig. 4). Large differences in soil water content were found at depths of 0.07–0.19 m in the untreated and treated plots between 17 May and 23 November 1999 (Fig. 4). In this zone, wet fingers and dry soil areas were evident in the soil profile in both the untreated and treated plots.

Surfactant treatment did not prevent irregular wetting of the water repellent subsoil. The variation in water content in the treated transects and soil blocks was also high, as demonstrated by the diagrams on the right-hand side of Fig. 4.

Irregular wetting patterns were also encountered at depths of 0.0825–0.1775 m in the soil blocks of the untreated and treated plots on 25 October 1999 (Fig. 6). Between 1 October and 25 October, precipitation amounted to 122 mm, yet soil...
was locally dry at depths of 0.0825–0.1775 m. Water content in these regions was generally <4 vol%. Rainwater flowed through the wet fingers in the soil, with water contents in these fingers between 10 and 25 vol%. The dry areas in these 2 blocks were extremely water repellent (compare Fig. 6 with Fig. 3).

Another 66 mm of rain fell before 23 November 1999. This rain event wetted the soil profiles distinctly, but dry patches remained at depths of 0.07–0.19 m in both the untreated and treated blocks. Surprisingly, the driest areas (water content of only 1–3 vol%) were found in the treated plot. More details concerning the spatial and temporal variability of the soil moisture content measured in the transects and soil blocks are given in Dekker et al. (2000).

In conclusion, Primer® 604 treatment appeared to slightly increase the mean water content of the water repellent soil profile to a depth of at least 0.19 m. The thatch layer of the treated plot was often found to have a higher moisture content than the thatch layer of the untreated plot. However, the surfactant did not improve the uneven moisture distribution in the soil below the surface layer. In this zone, movement of the surfactant was restricted to the preferential flow paths, and differences between lowest and highest soil water contents were larger in the treated plot than in the untreated plot.

**Critical soil water content**

Water content has a large effect on the actual water repellency of a soil (Dekker 1998). The concept of critical soil water content has been introduced by Dekker and Ritsema (1994) as the soil water content below which the soil is water repellent, and above which the soil is wettable. All samples taken from the thatch layer in the transects and soil blocks from the untreated plot between 17 May and 23 November 1999, and having a soil water content >23 vol%, were determined as wettable (Fig. 7, upper left-hand diagram). All samples with a soil water content <18 vol% were slightly to extremely water repellent with WDPT values of 5–60 s (class 1) up to 3–6 h (class 5). Soil samples with a water content of 18–23 vol% (grey zone) were assessed as either wettable or water repellent, introduced by Dekker et al. (2001) as the transition zone. This means that the...
critical soil water content of the thatch layer of the untreated plot is variable and ranges between 18 and 23 vol%, most likely depending on the wetting history of the soil, weather sequence, etc. The critical soil water content of the soil in the untreated plot at depths of 0.025–0.05 m was found to be between 14 and 19 vol% (Fig. 7, lower left-hand diagram). Although there were large differences in severity of actual water repellency at specific soil moisture contents, there was a distinct increase in severity with decreasing soil water contents, as shown in the diagrams of Fig. 7.

Treatment with Primer® 604 caused a significant decrease in the critical soil water content of the thatch layer, as can be seen in the upper right-hand diagram of Fig. 7. The transition zone varied in this case between 12 and 16.5 vol%, compared with variation between 18 and 23 vol% in the untreated plot. For instance, all soil samples with a water content of 17 vol% were determined as wettable in the Primer® 604-treated plot, whereas all samples with this water content in the untreated plot exhibited slight to extreme repellency. Also at depths of 0.025–0.05 m there was a slight shift in the critical soil water content. Soil samples with water contents of 8–14 vol% were water repellent in the untreated plot, whereas in the Primer® 604-treated plot a number of samples with these water contents were still wettable.

In conclusion, the critical soil water content in the thatch layer was lowered distinctly by the applications of Primer® 604. This means that the surfactant-treated soil dried to lower water contents than the untreated soil before water repellency was induced.

**Resistance to wetting of field-moist samples**

An instantly high wetting rate of the surface layer is important for the effective infiltration of rain and irrigation water as well as for prevention of erosion and runoff. Measurements with the wetting rate device showed that the water uptake of the thatch layer was generally more rapid in the beginning for samples from the plot treated with Primer® 604 than for samples from the untreated plot. Differences in instant wetting rate were observed between thatch layer samples from the untreated and treated plot on 5 of the 6 sampling dates (Fig. 8). The uptake of water (in mm) gives an indication of the amount of rainwater that can be absorbed readily. It is evident from the diagrams that water infiltrated more effectively into the thatch layer of the treated plot than the control. Initial soil water content of the samples played an important role for the wetting rate during the first hour (Fig. 8). Especially, samples from the untreated plot with soil water contents below the critical soil water content exhibited less affinity for water absorption.
Note that the wetting rate of the thatch layer did not increase after the first Primer® 604 application, as shown by the diagram of 17 May 1999, but a distinct increase was observed after additional applications, as shown by the diagrams of 16 June–21 September 1999 (Fig. 8).

In conclusion, the application of Primer® 604 increased the wetting rate of the thatch layer, which results in a more effective wetting of the root-zone during rain events and/or irrigation events, thereby decreasing runoff.

Persistence of potential water repellency

The persistence of potential water repellency of samples taken at depths of 0–0.025 and 0.025–0.05 m both in the transects and in the soil blocks of the untreated and treated plots was measured with the WDPT test after drying at 25°C. All field-moist samples from the 22 April 1999 transect were wettable, but the WDPT varied between 60–600 s (class 2) and 3–6 h (class 5) after drying at 25°C (data not shown). Differences in potential water repellency (samples dried at 25°C prior to WDPT) occurred between samples taken at the same depths but also between samples taken on different sampling dates (Fig. 9). Notable differences in persistence of water repellency were found between the 0–0.025 and 0.025–0.05 m depths in the untreated plot between the 2 September and 12 October 1999 transects. All samples from 2 September 1999 exhibited extreme water repellency with WDPTs between 1–3 and >6 h, whereas the 12 October 1999 samples showed strong to severe water repellency with WDPTs varying between 60 s and 1 h (Fig. 9). High spatial and temporal variability in potential water repellency were also determined for the samples taken at depths of 0.025–0.05 m in the
treated plot between 17 May and 23 November 1999, as demonstrated in Fig. 9. Because all samples were dry, the differences in water repellency must be due to differences in initial water content of the samples and a process of initiating water repellency in the field. The persistence of potential water repellency of the samples dried at 25°C is clearly negatively related to the initial soil water content and positively to the persistence of the actual water repellency of the samples. For example, the relatively dry and severe to extreme actual water repellency of the 17 May and 2 and 21 September 1999 transects (Fig. 1) resulted in locally extreme potential water repellency (Fig. 9).

Fig. 9. Relative frequency of the persistence of potential water repellency of samples dried at 25°C, and taken at depths of 0–0.025 and 0.025–0.05 m in the untreated and treated dune sand on 9 sampling days (for n see Fig. 1).

Distinctly lower WDPT values after drying at 25°C were detected for the samples taken at both depths in the Primer®604-treated plot between 1 June and 23 November 1999 compared with the untreated plot (Fig. 9). A majority of the samples taken from the thatch layer of the treated plot between 8 July and 25 October 1999 exhibited only slight water repellency after drying at 25°C, whereas most samples from the untreated plot exhibited severe to extreme water repellency (Fig. 9).

In most cases the persistence of potential water repellency of the samples was distinctly higher than the actual water repellency after the samples had been dried at 25°C.
However, it is worthy of note that the potential water repellency of samples on some days was less severe than the actual water repellency of field-moist samples on other days, thus underestimating the maximal persistence of water repellency that can occur in the field (see Fig. 1 and Fig. 9). This indicates that processes which are taking place in the field during dry weather cannot be artificially generated during drying in a laboratory oven over a time span of several days. Regardless of how water repellency was measured in soil samples, surfactant treatment generally shifted water repellency classes (actual or potential) to more wettable classes. Surfactant-induced shifts in water repellency classes were most evident in potential water repellency results.

In conclusion, the spatial and temporal variability in persistence of water repellency after drying at 25°C was high at both depths for the treated and untreated plot. But more important, distinctly lower WDPT values were detected for samples at depths of 0–0.025 and 0.025–0.05 m from the Primer®604-treated plot than the untreated plot.

**Discussion and conclusions**

Water repellency of soils may dramatically affect water and solute movement, due to non-uniform wetting and forming of preferential flow paths, so-called fingers, as also often occur in the dune sand studied. Soil wetting agents have been developed as a possible means for overcoming the problems caused by water repellency (e.g. Kostka et al. 1997; Cisar et al. 2000). It is evident that a test of the effectiveness of a soil wetting agent must include the assessment of the uniformity of distribution of the water in the soil. Soil moisture measurements in the untreated plot and in the treated plot with applications of Primer®604 revealed that after rain events the thatch layer in the treated plot was wetter than the untreated control. However, the applications did not improve the uneven distribution in the soil below the surface layer. The differences between lowest and highest soil water contents were even larger in the treated plot than the untreated plot.

A more homogeneous wetting of the treated soil may be realised by using a surfactant that penetrates deeper into the soil profile, or by combining treatments with sprinkler irrigations to prevent drying of the soil below the critical soil water content, and thereby preventing the soil from becoming water repellent. This is in accordance to the statement of Moore (1981): ‘Once an area receives an effective wetting agent program and has a treated root-zone, surface applied rain and irrigation penetrates rapidly, wets and drains through thatch, and uniformly wets the entire profile’.

The variability in actual water repellency was high over short distances at all depths in the untreated and treated dune sand, with WDPT values often varying between <5 s and >6 h on all sampling days (Fig. 1, Fig. 2). Relatively small differences in actual water repellency between the untreated and treated plot were determined for samples collected at depths of 0.07–0.19 m (Fig. 2). Applications of Primer®604 resulted in less persistent water repellency in the thatch layer and surface layer to a depth of 0.05 m (Fig. 1).

Water content has a large effect on the actual water repellency of a soil. The critical soil water content introduced by Dekker and Ritsema (1994) appears not to be a sharp static threshold above which a soil is wettable and below which a soil is water repellent, but rather a transitional range value. This range of critical soil water contents for a certain depth has been introduced by Dekker et al. (2001) as the ‘transition zone’. Soil samples can be either wettable or water repellent within the transition zone, depending on the wetting history, sequence of weather conditions, etc. In the untreated plot of the dune sand studied the transition zone was assessed at depths of 0–0.025 and 0.025–0.05 m as being between soil water contents of 18–23 and 14–20 vol%, respectively. Applications of Primer®604 lowered these transition zones to 12–16.5 and 8–20 vol%, respectively (Fig. 7). This implies that the surface layer in the treated soil can dry to lower water contents than in the untreated soil before water repellency is induced.

Primer®604 applications also increased distinctly the wetting rate of the field-moist samples from the thatch layer (Fig. 8). This may result in a more effective supply of water (irrigation), thereby inducing a better grass growth and a reduction in runoff.

The spatial and temporal variability in persistence of potential water repellency after drying at 25°C was high at depths of 0–0.025 and 0.025–0.05 m in the treated and untreated plot (Fig. 9). More important, distinctly lower WDPT values were detected for the samples from the Primer®604-treated plot compared with the untreated plot.

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