Effects of Surfactant Treatments on the Wettability of the Surface Layer and the Wetting Patterns in a Water Repellent Dune Sand with Grass Cover

Louis W. Dekker
Klaas Oostindie
Coen J. Ritsema

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Louis W. Dekker
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Abstract


This study evaluates the effectiveness of a new surfactant formulation (Primer®604) for amelioration and management of soil water repellency in a dune sand, as measured with the water drop penetration time (WDPT) test, and soil moisture content and wetting rate assessments. A dune sand with grass cover with a history of extreme water repellency was treated with 185 ml of surfactant (in 7 l of water) per 100 square m. Treatment was applied three weekly from 22 April until 23 November 1999. Soil samples were taken at six depths in trenches in the treated and untreated plot over a seven-month period beginning with the initial treatment application on 22 April 1999. Surfactant treatment significantly reduced soil water repellency in the surface layer of the plot when compared with the untreated control. As a consequence an increase in the wetting rate and higher soil water contents have been found for the surface layer of the treated plot. However, the surfactant did not improve the uneven moisture distribution in the soil below the surface layer.

Keywords: actual water repellency, potential water repellency, critical soil water content, water drop penetration time (WDPT) test, alcohol percentage test

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Summary

The problem of soil water repellency has been recognized in various parts of the world and has caused serious land use problems in sandy soils with grass vegetation.

The objective of this study was to evaluate the effectiveness of a new surfactant formulation Primer®604 (Aquatrols, Cherry Hill, New Jersey, U.S.A.) for amelioration and management of soil water repellency in a grass-covered dune sand. The wetting agent was applied on a plot of 25 m x 5 m on a dune sand near Ouddorp, in the southwestern part of the Netherlands. An untreated adjacent plot was used for comparison. The soil is known to be severely to extremely water repellent to a depth of more than 50 cm during dry periods. Primer®604 was applied at a rate of 1.85 ml/m² (volume solution 70 ml/m²) twelve times during the period 22 April to 23 November 1999.

During that period the soil of the untreated and treated plot was sampled eight times in trenches and two times in soil blocks. Samples were taken at six depths (0-2.5, 2.5-5, 7-9.5, 9.5-12, 14-16.5, and 16.5-19 cm) using steel cylinders, with a diameter of 5 cm. A total of 4950 samples have been collected for measuring the actual water repellency of field-moist samples, the spatial and temporal variability of the soil water content, and the potential water repellency after drying the samples at 25°C, 65°C, and 105°C. The persistence or stability of water repellency of the soil samples was examined using the water drop penetration time (WDPT) test.

The degree of potential water repellency was measured on all samples taken in the four soil blocks on 25 October and 23 November 1999, using the alcohol percentage test. To study the influence of drying temperature on the degree of water repellency, measurements were performed on soil samples dried at 25°C, and after further drying at 65°C and 105°C.

Resistance to wetting was determined by measuring the wetting rate of field-moist and dried samples. Measurements of actual water repellency on field-moist samples revealed that the applications of Primer®604 resulted into less persistent water repellency in the surface layer to a depth of 5 cm. No positive effects of surfactant treatment could be observed deeper in the soil profile.

The critical soil water content, below which the soil is actually water repellent in the field, was lowered significantly by the application of Primer®604 for the surface layer at depths of 0-5 cm. This means that the soil in the Primer treated plot may dry to a lower water content than the surface layer of the untreated plot before water repellency is induced.

Applications of Primer®604 slightly increased the mean water content of the water repellent soil profile to a depth of at least 19 cm. 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, the differences between lowest and highest soil water contents were even larger in the treated plot when compared with the untreated plot. We note the uniqueness of this test site as it relates
to the extreme depths at which water repellency was found. This is very different from what is normally encountered in golf course soils.

Primer®604 applications increased the wetting rate of the field-moist samples from the thatch layer, especially at the start and during the first hour of wetting. This may result in a more effective wetting of the root zone during rain events and artificial supply of water (irrigation), thereby inducing a better grass growth and a reduction in runoff. Low wetting rates were assessed for numerous samples from different depths of both plots, with water contents below the critical soil water content. The water uptake of these water repellent samples was very slow during the first hour, and often nearly no water at all was absorbed.

Highly spatial and temporal variability in persistence of potential water repellency were determined for the samples taken at all six depths in the untreated and treated plot between 17 May and 23 November. 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. It is worthy of note that the actual water repellency on some days was more severe than the potential water repellency of dried samples on other days. Significantly lower WDPT values were detected for the samples dried at 25°C and taken at depths of 0-5 cm in the treated plot with Primer®604 between 1 June and 23 November, when compared with the untreated plot.

Soil samples from the thatch layer of the treated plot exhibited also significantly less persistent water repellency after drying at 65°C, when compared with the untreated plot. The persistence of water repellency of the soil samples increased significantly after drying at 105°C, in particular those from depths of 0-5 cm.

Primer®604 treatment resulted in significantly lower degrees of potential water repellency, as measured with the alcohol test, for samples taken on 25 October and 23 November from the thatch layer, after drying at 25°C and 65°C, when compared with samples from the untreated plot. Drying at 65°C did not clearly affect the degree of repellency, in comparison with 25°C, with the exception of an increase for samples from the treated thatch layer. However, drying at 105°C resulted in a significant increase in degree of potential water repellency for samples taken at depth of 0-12 cm in the untreated as well as the treated plot.

Wetting rate measurements of samples dried at 25°C revealed that the initial soil water content of the samples in the field is crucial for the wetting. Samples with initial high soil water content wet more rapidly, when compared with samples with initial low water content and exhibiting an actually water repellent behavior.

To conclude, regular applications of Primer®604 significantly increased infiltration rates into the water repellent soil surface. Observed soil water contents appeared to be higher than found in the untreated plot. Furthermore, the soil water content range in which water repellency might be induced in the field decreases due to regular Primer®604 applications. Effects of the applied surfactant treatment were restricted to the surface layer in this extremely water repellent soil.
1. Introduction

The problem of soil water repellency has been recognized in various parts of the world (Jaramillo et al., 2000) including the Netherlands (Dekker and Jungertius, 1990; Hendrickx et al., 1993; Dekker et al., 2000a) and has caused for instance serious land use problems in agriculture (Blackwell, 2000) and on turf (Cisar et al., 2000). Although more than 900 papers have been published on soil water repellency (DeBano and Dekker, 2000), there are still a lot of questions left to be answered concerning the origin, occurrence, assessment, consequences and improvement of this phenomenon.

It has been recognized for many years that water repellency of a soil is often a function of the type of organic matter incorporated in it, and that the organic matter induces water repellency in soils by several means. Firstly, irreversible drying processes in organic matter can induce water repellency, for instance in the surface layers of peat soils, which are difficult to rewet after drying (e.g. Hooghoudt, 1950; Dekker and Ritsema, 1996b). Secondly, plant decomposition compounds like certain organic substances can induce water repellency in sandy soils (DeBano, 2000). Thirdly, hydrophobic microbial by-products coating mineral soil particles may induce wetting resistance (Doerr et al., 2000). Fourthly, mineral particles need not to be individually coated with hydrophobic materials; intermixing of mineral soil particles with particulate organic matter, like remnants of roots, leaves and stems, may also induce severe water repellency (Bisdom et al., 1993). Sporadically, soil water repellency might be induced by presence of algae and/or fungi (Doerr et al., 2000).

![Image](image-url)

**Figure 1** Nonuniform wetting in the dune sand with grass cover at the Ouddorp site.
Water repellency may dramatically affect water and solute movement at the field-scale, which has often been underestimated (Ritsema and Dekker, 1998; Bauters et al., 2000). Water repellency and its spatial variability have been shown to cause nonuniform wetting and preferential flow (Fig. 1) in many field soils (Dekker and Ritsema, 1994; 1996b; 2000; Ritsema and Dekker, 1996; Ritsema et al., 1998b; Wang et al., 2000).

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 and moves laterally toward 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 all subsequent transport (Ritsema and Dekker, 1995).

Soil wetting agents have been developed as a possible means for overcoming the problems caused by water repellent soils (Letey et al., 1962; Moore, 1981; Rieke, 1981; Michel et al., 1997; Dekker et al., 2000b, 2001; Kostka et al., 1997; Kostka, 2000). Provided that the wetting agent has a strong affinity with both the hydrophobic soil particles and water molecules, strong adsorption of the wetting agent at the soil surface would 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 a new surfactant formulation (Primer®604) for amelioration and management of soil water repellency in turfgrass on a native dune sand. This study was supported by Aquatrols Corporation of America, Cherry Hill, New Jersey, U.S.A. The present report describes the influence of the surfactant on reducing the severity of soil water repellency, the increase in wetting rate, and the influence on the spatial variability in soil water content, water flow, and wetting patterns.
2. Materials and Methods

2.1. Field-soil and Treatment

A wetting agent was applied to a 25 m x 5 m plot of a dune sand near Ouddorp in the southwestern part of the Netherlands. An untreated adjacent plot was used for comparison. The soil consists of fine sand with less than 3% clay to a depth of more than 3 m, and is classified as mesic Typic Psammaquent (Dekker, 1998). The site is grass-covered, is in use as pasture, and has not been tilled for at least several decades. Organic matter contents of 18 and 10 w% were established in the thatch layer at depths of 0-2.5 and 2.5-5 cm, respectively. At depths of 5-7.5 cm an organic matter content of 2 w% was found, and from 7.5 cm downwards of around 0.5 w%. The soil is known to be severely to extremely water repellent to a depth of more than 50 cm during dry periods (Dekker and Ritsema, 1994; Dekker et al., 2000a).

Treatments with Primer@604 (Aquatrols Corporation of America, Cherry Hill, New Jersey, U.S.A.) at a rate of 1.85 ml/m² (volume solution 70 ml/m²) were applied with a Mesto Pico backpack-type sprayer, twelve times during the period 22 April to 23 November 1999.

2.2. Soil Sampling

Between 22 April and 12 October 1999 the spatial and temporal variability in volumetric soil water content was studied eight times in vertical transects by intensive sampling of the treated and the untreated plot. For a better understanding of the dimensions of the wetting patterns in the dune sand, soil blocks were sampled in both plots on 25 October and 23 November 1999. The soil from trenches and blocks was sampled at six depths (0-2.5, 2.5-5, 7-9.5, 9.5-12, 14-16.5, and 16.5-19 cm) using steel cylinders, with a diameter of 5 cm. In the trenches at each depth, 35 samples were taken in close order over a distance of about 1.8 m. A total of 15 times 210, or 3150 samples, had been collected in the trenches. In the soil blocks at each depth 75 samples were taken in a regular grid of 15 by 5 samples, and a total of 4 times 450 samples were collected. The cylinders were pressed vertically into the soil, emptied into plastic bags and used again. The plastic bags were tightly sealed to minimize evaporation from the soil. The field-moist soil in the plastic bags was weighed, the actual water repellency was measured, the samples were dried at 25°C, after which the potential water repellency was measured. The samples were further dried at a temperature of 65°C, and weighed again to calculate the water content and dry bulk density of the samples. A total of 4950 samples have been collected and measured in this way.

2.3. Water Drop Penetration Time (WDPT) Test

The persistence or stability of water repellency of the soil samples was examined using the water drop penetration time (WDPT) test. Three drops of distilled water from a standard medicine dropper were placed on the smoothed surface of a soil sample, and the time that elapses before the drops were absorbed was determined (Fig. 2). We measured the soil water repellency of all 4950 samples 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 repellant if the WDPT exceeds 5 s (Dekker, 1998). We applied an index allowing a quantitative definition of the persistence of soil water repellency as described by Dekker and Jungerius (1990). In the present study seven classes of repellency were distinguished, based on the time needed for the water drops to penetrate into the soil: class 0, wettable, non-water repellant (infiltration within 5 s); class 1, slightly water repellant (5 to 60 s); class 2, strongly water repellant (60 to 600 s); class 3, severely water repellant (600 s to 1 h); and extremely water repellant (more than 1 h), further subdivided into class 4, 1 to 3 h; class 5, 3 to 6 h; and class 6, >6 h.

We measured the water repellency of the field-moist samples and after drying at 25, 65 and 105°C. The severity of water repellency measured on dried soil samples, the so-called “potential” water repellency, can be used as a parameter for comparing soils with respect to their sensitivity to water repellency. Measurements of the “actual” water repellency on the field-moist samples were performed immediately after assessment of the wet weights. Because we also measured the water content of the samples, we could assess “critical soil water contents” for the different depths of the intensively sampled trenches and soil blocks. The soil is wettable above, and water repellant below these values.

Figure 2 Water repellency measurement (WDPT test) by placing three drops of water upon the surface of a soil sample and determining the time to complete absorption.
2.4. Alcohol Percentage Test

The fundamental principles underlying the process of wetting show that a reduction in the surface tension of a solid substance which is to be wetted reduces its wettability. Conversely, a reduction in the surface tension of the applied liquid increases the wettability. The study of repellency amelioration requires appropriate measurement techniques to be used. Over the years many techniques have been developed to measure water repellency. One of the simplest and most common methods of classifying water repellency is the (WDPT) test, as described before. Another common method is the alcohol percentage test (Watson and Letey, 1970).

Water containing increasing concentrations of ethanol is applied in drop form to the surface of soil samples until a concentration is reached where infiltration occurs within 5 s. At this concentration, the aqueous ethanol drop has a sufficiently low surface tension to overcome the surface water repellency restriction to infiltration. If a high concentration of ethanol is required for incipient infiltration, this is indicative of hydrophobic soils.

We measured the degree of water repellency of all the samples taken in the four soil blocks on 25 October and 23 November 1999, using the following alcohol percentage test. We used bottles with solutions containing 1, 2, 3, 4, 5, 6, 8, 10, 12.5, and 15% and with increments of 2.5% to 35% of ethanol on a volume basis. Alcohol percentage tests were conducted on the dried samples, thus measuring the degree of potential water repellency. The samples were first dried at 25°C; and later at 65°C and 105°C, to study the effect of the drying temperature on the severity of water repellency, as was also studied for several other soils in the Netherlands by Dekker et al. (1998). Because temperature and relative air humidity affect the obtained values, the measurements were performed under laboratory conditions with a constant temperature of 20°C and a relative humidity of 50%. Alcohol percentage tests were deferred for at least 2 days to obtain samples in equilibrium with the ambient air humidity.

2.5. Wetting Rate Measurements

Resistance to wetting was determined several times by measuring the wetting rate (Fig. 3) of field-moist samples collected at depths of 0-2.5, 2.5-5.0, 7.5-9.5, 9.5-12, 14-16.5, and 16.5-19 cm in the treated and untreated plot of the Ouddorp site, prior to treatment applications. Additional samples were also collected and oven-dried at a temperature of 25°C. The samples were taken with the help of steel cylinders (50 cm³) with a height of 2.5 cm and a diameter of about 5 cm.

These samples, within their steel cylinders, were subjected to a constant pressure head of ~2.5 cm water applied to the bottom of the samples (Dekker, 1998). The experimental set-up was designed in such way that water content increments of 1.0 vol% were recorded automatically over a period of one week. The measurements were performed in a conditioned laboratory with a constant temperature of 20°C and a relative air humidity of 50%.
Figure 3 Measurement of the wetting rate of eight soil samples, placed on ceramic filters and subjected to a pressure head of ~2.5 cm water at the bottom of the samples. During the measurements the water level in the basin is kept constant. The water uptake of the samples is recorded by the balances and stored by the computer.

Figure 4 Relative frequency of the persistence of actual and potential water repellency (after drying at 25, 65, and 105°C) of samples (n = 35) taken at six depths in the 22 April trench.
Figure 5: Relative frequency of the persistence of actual water repellency of field-moist samples taken at six depths in the untreated dune sand on nine sampling days (n = 35 at all depths for the 17 May to 12 October trenches, and n = 75 for the 25 October and 23 November soil blocks).
Figure 6 Relative frequency of the persistence of actual water repellency of field-moist samples taken at six depths in the dune sand plot treated with surfactant on nine sampling days (for number of samples see Fig. 5).
3. Results

3.1. Actual water repellency

The whole soil profile was moist to wet at the start of the experiment on 22 April 1999. All 210 samples taken at depths between 0 and 19 cm were actually wettable or non-water repellent, exhibiting WDPT values of less than 5 s, as shown in the top left diagram of Figure 4.

In the period that followed the field-soil dried and all samples taken on 17 May at depths between 0 and 16.5 cm and the largest part of the samples at depths of 16.5-19 cm had become actually water repellent (see Figs. 5, 6). The repellency of the surface layer at depths of 0-2.5 cm varied between 60 s and 3h. The severity of water repellency in the soil profile increased with depth towards 12 cm. At depths of 9.5-12 cm about 65% of the samples from the untreated as well as from the treated plot revealed WDPT values exceeding 6 h (Figs. 5, 6). A decrease in severity of actual water repellency occurred in the layers sampled below 12 cm.

The variability in actual water repellency was high in the soil at short distances at all depths in the untreated and treated plot, with WDPTs often varying between less than 5 s to more than 6 h on all sampling days (Figs. 5, 6). Relatively small differences in actual water repellency between the untreated and treated plot were determined for samples collected at depths of 7 to 19 cm. The surface layer (0-2.5 cm depth) was found to be wettable for both plots on 22 April, 12 August, 12 and 25 October, and 23 November. More wettable samples were recorded in the surface layer of the treated plot in comparison with the untreated plot on 1 June and 8 July. Significantly lower WDPTs were recorded for the samples taken in the surface layer and at depths of 2.5-5 cm in the treated plot when compared with the untreated plot on 2 and 21 September.

The spatial and the temporal variability of actual water repellency in trenches of the untreated (Fig. 7) and treated plot (Fig. 8) are remarkable. Dry soil pockets with extreme water repellency, and preferential flow paths (fingerns) with wettable soil, were detected over a horizontal distance of only 1.8 m. This was, for instance the case in the 2 September and 12 October trenches of the untreated plot (Fig. 7) and in the 1 June, 8 July, and 2 September trenches of the treated plot (Fig. 8). The temporal variability in actual water repellency of the soil in both plots is evident when comparing the diagrams of the trenches dug at different times.

Spatial variability in severity of actual water repellency is demonstrated by the contour plots of the October and November soil blocks, with a size of only 0.75 m x 0.25 m x 0.19 m, or 0.036 m³. It is worthy of note, that the actual water repellency at depths of 7-19 cm in the treated plot was more severe and distributed over larger areas when compared with the untreated plot on 25 October (Figs. 9, 10) as well as on 23 November (Figs. 11, 12). Although the severity of actual water repellency decreased during the autumn rains, extreme repellency with WDPTs of more than 1 h, still occurred in dry soil pockets (Figs. 11, 12).

In conclusion, the application of Primer®604 resulted in less persistent water repellency in the surface layer to a depth of 5 cm, but no positive effects could be observed deeper in the profile.
Figure 7 Contours of the persistence of actual water repellency of field-moist samples in five trenches sampled in the untreated dune sand plot.
Figure 8 Contours of the persistence of actual water repellency of field-moist samples in five trenches sampled in the dune sand plot treated with Primer® 604.
Figure 9 Contours of the persistence of actual water repellency in horizontal planes (25 cm x 75 cm) at six depths from the untreated and treated 25 October soil blocks.
Figure 10 Contours of the persistence of actual water repellency in five vertical planes (side views) from the untreated and treated 25 October soil blocks.
Figure 11 Contours of the persistence of actual water repellency in horizontal planes (25 cm x 75 cm) at five depths from the untreated and treated 23 November soil blocks.
Figure 12 Contours of the persistence of actual water repellency in five vertical planes (side views) from the untreated and treated 23 November soil blocks.
Figure 13 Mean soil water contents in the topsoil of the treated and untreated plots on nine sampling days.
3.2. Soil Water Content

The spatial variability of the soil water content was often found to be high in all layers sampled. The highest water contents were found in the surface layers, which have higher organic matter contents and lower dry bulk densities when compared with the deeper layers. Relatively high soil water contents were established at depths of 0.5 cm in April, October and November, however also then the spatial variability was high. For instance, the soil water content at depths of 0-2.5 cm varied between 31.4 and 69.3 vol%, and at depths of 2.5-5 cm 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 water content of the thatch layer (0-2.5 cm) varied in the treated plot between 31.5 and 54.3 vol% and in the untreated plot between 33.7 and 47.5 vol%.

The soil in the thatch layer at depths of 0-2.5 cm in the treated plot was often wetter in comparison with the untreated plot. For example, the mean soil water content in the treated plot amounted to 43.8 vol% at depths of 0-2.5 cm on 25 October, compared with 40.8 vol% in the untreated plot. The mean soil water contents of the plot with Primeq0604 applications, exhibited slightly higher values when compared with the untreated plot at all depths and almost in all trenches sampled (Fig. 13). The diagrams of this figure also show clearly the huge difference in water content between the surface layer and the soil about 10-20 cm deep.

Relatively dry trenches were sampled on 17 May and 2 September 1999. Huge differences in soil water content were found at depths of 5-19 cm in the untreated as well as treated plot between 17 May and 23 November. In this zone, wet fingers and dry soil bodies were evident in the soil profile of both plots all the time.

The spatial variability in soil water content of five trenches in the untreated plot is shown in Figure 14. The water content differed slightly in horizontal direction in the wet surface layer and in the dry subsoil of the 8 July trench, but the spatial variability was large at depths of 7-19 cm in the 12 October trench. In succession wet fingers and dry soil bodies were present at these depths.

The applications of the surfactant did not prevent irregular wetting of the water repellent dune sand. The variation in water content in the trenches was often high, as demonstrated by the contours in the five trenches presented in Figure 15.

Irregular wetting patterns were also detected at depths of 7-19 cm in the soil blocks of the untreated and treated plots on 25 October 1999 (Fig. 16). Although between 1 October and 25 October the precipitation amounted to 122 mm, the soil was locally dry at depths of 7-19 cm, with water contents of less than 4 vol%. Rain water flowed through the wet fingers in the soil, with water contents between 10 and 25 vol%, as is shown by the contours in the vertical planes of the soil blocks in Figure 17. The dry areas in these two blocks were partly extremely water repellent (compare Figs. 15, 16 with Figs. 9, 10).

Another 66 mm of rain that fell before the sampling on 23 November wetted the soil profiles clearly, but still dry patches occurred at depths of 7-19 cm in the untreated and treated soil blocks (Figs. 18, 19). Surprisingly, the driest pockets, with water contents of only 1-3 vol% were established in the treated plot.
Figure 14 Contours of the soil water content in five trenches sampled in the untreated dune sand plot.
Figure 15 Contours of the soil water content in five trenches sampled in the treated dune sand plot.
Figure 16 Contours of the volumetric soil water content in horizontal planes (25 cm x 75 cm) at six depths in the untreated and treated dune sand on 25 October 1999.
Figure 17: Contours of the volumetric soil water content in five vertical planes (side views) in the untreated and treated dune sand on 25 October 1999.
Figure 18 Contours of the volumetric soil water content in horizontal planes (25 cm x 75 cm) at five depths in the untreated and treated dune sand on 23 November 1999.
Figure 19 Contours of the volumetric soil water content in five vertical planes (side views) in the untreated and treated dune sand on 23 November 1999.
Figure 20 Relationship between the soil water content and the persistence of the actual water repellency in the thatch (0-2.5 cm) and deeper surface layer (2.5-5 cm) of the untreated dune sand.
In conclusion, the applications of Primer®604 slightly increased the mean water content of the water repellent soil profile to a depth of at least 19 cm. 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. The differences between lowest and highest soil water contents were even larger in the treated plot when compared with the untreated plot.

3.3. Critical Soil Water Content

Water content has a large effect on the actual water repellency of a soil (Letey et al., 1962; Gilmour, 1968; Dekker, 1998). The critical soil water content has been introduced by Dekker and Risiena (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 trenches and soil blocks from the untreated plot between 17 May and 21 November 1999, and having a soil water content above 23 vol%, were determined as wettable (Fig. 20, upper diagram, blue zone). All samples with a soil water content of less than 18 vol% (pink zone) 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 between 18 and 23 vol% (yellow zone) were assessed as either wettable or water repellent, introduced here 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%.

The critical soil water content of the soil at depths of 2.5-5 cm in the untreated plot was assessed between 14 and 19 vol% (Fig. 20, lower diagram, yellow zone). At depths of 7-9.5, 9.5-12, 14-16.5, and 16.5-19 cm, the critical soil water contents were assessed between 4-8.5, 3-6.5, 2.5-6, and 2-5 vol%, respectively (Fig. 21). Thus, the critical soil water content tends to be lower at greater depths. This decrease maybe due to a decrease with depth of the organic matter content, resulting in different water retention curves. Although there are large differences in severity of actual water repellency at specific soil moisture contents, there is a distinct increase in severity with decreasing soil water contents, as shown in the diagrams of Figures 20 and 21.

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 diagram of Figure 22. The transition zone varied in this case between 12 and 16.5 vol%, whereas a variation between 18 and 23 vol% was established for 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 2.5-5 cm there is a slight effect on the critical soil water content. Soil samples with water contents of 8-14 vol% are with one exception water repellent in the untreated plot, whereas in the Primer®604 treated plot a part of samples with these water contents are still wettable. The influence from the treatment with surfactant upon the critical soil water contents at greater depths was not significant as can be seen by comparing the diagrams of Figure 23 with those of Figure 21.
Figure 21 Relationship between the soil water content and the persistence of the actual water repellency at four depths in the untreated dune sand.
Figure 22 Relationship between the soil water content and the persistence of the actual water repellency in the thatch (0-2.5 cm) and deeper surface layer (2.5-5 cm) of the dune sand treated with Primer®604
Figure 23 Relationship between the soil water content and the persistence of the actual water repellency at four depths in the dune sand treated with Primer®604.
Figure 24 Transition zone with critical soil water contents for the soil profiles to about 20 cm depth in the untreated (top diagram) and treated (bottom diagram) dune sand. In the diagram of the untreated (treated) plot the lines of the transition zone of the treated (untreated) plot are given.
Figure 25 Increase in water content of field-moist samples taken at six depths on 22 April 1999. The samples are placed at a constant pressure head of –2.5 cm water applied at the bottom of the samples during one week.
The transition zone with critical soil water contents at depths between 0 and 19 cm in the untreated and Primer®604 treated soil profiles are given in Figure 24 (yellow zones). The pink zones in the diagrams represent the actually water repellent and the blue zones the actually wettable zones in relation to depth and soil water content. The lines with boundaries of the transition zone of the treated soil are given in the diagram of the untreated plot, and on the other hand those of the untreated soil in the diagram of the treated plot, for comparison.

In conclusion, the critical soil water content in the thatch layer has been lowered significantly by the applications of Primer®604. This means that the treated soil can dry to lower water contents before water repellency is induced in comparison with the untreated soil.

3.4. Resistance to Wetting of Field-moist Samples

Measurements (during one week) of the wetting rate of field-moist samples taken at six depths on 22 April 1999, prior to the first application of Primer®604, are shown in Figure 25. Because all samples from this date were wettable, the wetting rates were very high during the first hour of wetting and decreased thereafter. The soil water contents of the samples varied after 7 days wetting between 70 vol% for the thatch layer to 31 vol% at depths of 16.5-19 cm. The decrease in soil water content with depth is related to the decrease in organic matter content and the increase in dry bulk density with depth. For instance, the dry bulk density of the sample from 0-2.5 cm was 0.72 g cm⁻³ and from 16.5-19 cm 1.59 g cm⁻³.

The increases in water content after 1 h and 24 h wetting of field-moist samples taken at depths of 0-2.5 cm and 2.5-5 cm in the untreated and treated plot between 22 April and 12 October 1999 are illustrated in the diagrams of Figure 26. Significantly better wetting was found for the samples taken in the treated plot on 8 and 27 July, when compared with the untreated plot.

Many samples taken at depths between 7 and 19 cm in the untreated and treated plot wetted very slowly, especially during the first hour of wetting, but often also during the 23 h that followed, as is shown in Figure 27 and Figure 28.

Figure 29 shows that the initial soil water content of the samples from the surface layer played an important role for the wetting rate during the first hour. Especially, samples with soil water contents below the critical soil water content (pink and part of yellow zones), exhibited less affinity for water absorption. Figure 29 gives clear evidence that more field-moist samples from the thatch layer of the treated plot had water contents above the critical soil water content, when compared with the untreated plot. Hence the wetting of a larger number of samples is faster during the first hour. Because more samples from the treated plot at depths of 2.5-5 cm had water contents corresponding with the transition zone instead of the repellent zone, when compared with the untreated plot, the wetting of the samples from the plot with Primer®604 applications was clearly better during the first hour.

Most samples taken at depths of 7-9.5 and 9.5-12 cm in the untreated and treated plot between 17 May and 12 October had soil water contents below the respective critical soil water contents. The repellent behavior of these samples resulted in a worse wetting during the first hour, as is illustrated in Figure 30.
Figure 26 Increase in water content of field-moist samples taken at depths of 0-2.5 and 2.5-5 cm in the untreated and treated plot between 22 April and 12 October 1999, after 1 and 24 h application of water at the bottom of the samples.
Figure 27 Increase in water content of field-moist samples taken at depths of 7-9.5 and 9.5-12 cm in the untreated and treated plot between 22 April and 12 October 1999, after 1 and 24 h application of water at the bottom of the samples.

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Figure 28 Increase in water content of field-moist samples taken at depths of 14-16.5 and 16.5-19 cm in the untreated and treated plot between 22 April and 12 October 1999, after 1 and 24 h application of water at the bottom of the samples.
Figure 29 Increase in water content of field-moist samples taken at depths of 0-2.5 and 2.5-5 cm in the untreated and treated plot after 1 h application of water at the bottom of the samples. The pink and yellow colors in the drawings represent the actually water repellent zones and transition zones, respectively.
Figure 30  Increase in water content of field-moist samples taken at depths of 7.9.5 and 9.5-12 cm in the untreated and treated plot after 1 h application of water at the bottom of the samples. The pink and yellow colors in the drawings represent the actually water repellent zones and transition zones, respectively.
Figure 34: Increase in water content of field-moist samples taken at depths of 12-14.5 and 14.5-16 cm in the untreated and treated plot after 1 h application of water at the bottom of the samples. The pink and yellow colors in the drawings represent the actually water repellent zones and transition zones, respectively.
Figure 32 Increase in water content (vol%) of field-moist samples from the untreated and treated thatch layer (0-2.5 cm) during 1 h wetting. The water uptake in mm is also indicated.
With the exception of two samples from 22 April and three from 2 September, all samples taken at depths of 14-16.5 and 16.5-19 cm in the untreated and treated plot had water contents in the pink zones or lower parts of the yellow zones, as shown in Figure 31. The water uptake of these actually water repellent samples was very slow during the first hour of wetting, as is evident from the diagrams of Figure 31.

An instantly high wetting rate of the surface layer is important for the effective infiltration of rain and irrigation water for plant growth as well as to prevent erosion and runoff. During the first time of water application the wetting of the thatch layer (0-2.5 cm) was generally more rapid for samples from the plot treated with Primer®604, than for samples from the untreated plot. Figure 32 demonstrates the difference in instant wetting rate between samples from the thatch layer of the untreated and treated plot, collected on six sampling days. The uptake of water in mm gives an indication of the amount of rainwater, which can be absorbed easily. It is evident from the diagrams that the thatch layer (0-2.5 cm) of the treated plot more effectively absorbed water.

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 application, thereby inducing a better grass growth and decreasing runoff.

3.5. Persistence of Potential Water Repellency

The persistence of potential water repellency of samples taken in the trenches and sail blocks of the untreated and treated plot was measured with the WDPT test after drying at 25°C, and after further drying at 65°C, and at 105°C.

All samples from the 22 April trench were actually wettable, but the WDPT varied between 60-600 s (class 2) and 3-6 h (class 5) after drying at 25°C, as shown in Figure 4. A slight increase was established after a further drying of the samples at 65°C. A remarkable increase in the persistence of potential water repellency was found after drying at 105°C. Most samples at depths of 2.5-19 cm did not absorb the water drops within 6 h (Fig. 4).

3.5.1. After drying at 25°C

Differences in potential water repellency after drying at 25°C occurred between samples taken at the same depths but also at different sampling dates. For example, there is a significant increase in persistence at all six depths for the samples from 17 May (Fig. 33), when compared with those of 22 April (Fig. 4). A further increase in the persistence of potential water repellency was found for the samples taken at depths of 7-19 cm on 1 June and 8 July, in comparison with the samples from 17 May.

Notable differences in persistence of water repellency were found for the surface layer at depths of 0-5 cm in the untreated plot between the 2 September and 12 October trench. All samples from 2 September exhibited extreme water repellency with WDPTs between 1-3 and > 6 h, whereas the 12 October samples showed strong to severe water repellency with WDPTs varying between 60-3600 s (Fig. 33). Because all samples were dry, the differences in water
Figure 33  Relative frequency of the persistence of potential water repellency (after drying at 25°C) of samples taken at six depths in 7 trenches and 2 soil blocks of the untreated plot. (n = 35 at all depths for the 17 May to 12 October trenches, and n = 75 for the 25 October and 23 November soil blocks).
Figure 34: Relative frequency of the persistence of potential water repellency (after drying at 25°C) of samples taken at six depths in 7 trenches and 2 soil blocks of the treated plot. (For n see Fig. 33).
Figure 35: Contours of the persistence of potential water repellency in 5 trenches of the untreated plot. The samples were dried in an oven at 25°C.
Figure 36: Contours of the persistence of potential water repellency in 5 trenches of the treated plot with Primer®604. The samples were dried at 25°C.
Figure 37 Contours of the persistence of potential water repellency in horizontal planes (25 cm x 75 cm) at six depths from the untreated and treated 25 October soil blocks. The samples were dried in an oven at 25°C.
Figure 38: Contours of the persistence of potential water repellency in five vertical planes (side views) from the untreated and treated 25 October soil blocks. The samples were dried in an oven at 25°C.
Figure 39 Relative frequency of the persistence of potential water repellency of samples from all trenches and soil blocks of the untreated and treated plot. The WDPT was assessed after drying at 65°C and after a further drying at 105°C.
due to differences in initial water content of the samples and a process of initiating water repellency in the field.

Highly spatial and temporal variability in potential water repellency were also determined for the samples taken at six depths in the treated plot between 17 May and 23 November, as is demonstrated in Figure 34.

Only slight differences in persistence of potential water repellency occurred between samples taken at depths of 7-19 cm in the treated plot, in comparison with the untreated plot. However, significantly lower WDPT values were detected for the samples taken at depths of 0-5 cm in the Primer®604 treated plot between 1 June and 23 November, when compared with the untreated plot (compare Fig. 34 with Fig. 33).

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 September trenches (Fig. 6) resulted in extreme potential water repellency (Fig. 34).

In some cases the persistence of potential water repellency of the samples was equal to the persistence of the actual water repellency, however in most cases the WDPTs increased significantly after the samples had been dried at 25°C (compare Fig. 33 with Fig. 5; and Fig. 34 with Fig 6).

It is worthy of note that the actual water repellency in the untreated plot at depths of 0-16.5 cm and in the treated plot at depths of 7-16.5 cm on some days was more severe than the potential water repellency measured after drying at 25°C (and 65°C) on other days. For example, the actual water repellency at depths of 0.2-5 cm and 2.5-5 cm in the untreated plot on 2 September was more severe than the potential water repellency of the samples taken on 22 April, 17 May, 12 October, and 26 November.

The samples collected in the untreated and treated plot at depths of 7-16.5 cm on 21 September exhibited also more extreme actual water repellency than the samples dried at several other dates, as can partly be concluded after comparing Figures 5 and 6 with Figures 33 and 34.

The spatial and temporal variability of the persistence of potential water repellency in the untreated plot is shown with 5 trenches in Figure 35. The increase in persistence of water repellency after drying and the relationship with the actual water repellency are evident by comparing Figures 35 and 7.

The spatial and temporal variation of the persistence of potential water repellency in the treated plot is shown with 5 trenches in Figure 36. The increase in persistence and the relation with the actual water repellency are clear when comparing Figure 36 with Figure 8.

The spatial variability in persistence of potential water repellency is illustrated with the contour plots of the 25 October soil blocks (Figs. 37 and 38). It is remarkably, that the potential water repellency at depths of 7-19 cm in the treated plot was more severe and distributed over larger areas, when compared with the untreated plot. However, in contrast was the potential repellency at depths of 0.5 cm in the untreated plot more severe than in the treated plot (Fig. 37). For comparison of these patterns of potential water repellency with those of the actual
Figure 40 Contours of the persistence of potential water repellency in five trenches of the untreated plot. The samples were dried in an oven at 65°C.
water repellency is referred to Figures 9 and 10.

In conclusion, the spatial and temporal variability in persistence of water repellency after drying at 25°C was high at all depths, both for the treated and untreated plot. Significantly lower WDPT values were detected for samples from depths of 0-5 cm from the Primer®604 treated plot, when compared with the untreated plot. The actual water repellency of the field-moist soil samples was on some days more severe than the potential water repellency of samples, measured after drying at 25°C in the laboratory, and taken on several other days. This indicates that processes taking place in the field during drying weather can not be artificially generated during drying in a laboratory oven over a time span of several days.

3.5.2. After drying at 65°C and 105°C

The relative frequency of the persistence of water repellency measured after drying all samples collected in the untreated and treated plot at 65°C; and 105°C is given in the diagrams of Figure 39. Only the thatch layer of the treated plot exhibited significant less repellency after drying at 65°C, when compared with the untreated plot, and no significant differences existed deeper in the profile. The persistence of the potential water repellency increased significantly at all depths after further drying of the samples at 105°C, and no differences could be assessed between samples from the treated and untreated plot. An exceptional increase in persistence of water repellency occurred after drying at 105°C for samples taken at depths of 0-5 cm in the untreated, and in particular in the treated plot.

The persistence of potential water repellency of the samples from depths of 7-19 cm in the untreated and treated plot were for most samplings nearly the same after drying at 25°C, and after drying at 65°C. The persistence of repellency after drying at 25°C and 65°C of the samples taken at depth of 0-5 cm, in the untreated as well as in the treated plot, was sometimes equal, but other times higher or lower WDPT values were determined after drying at 65°C.

The spatial and temporal variability of the persistence of potential water repellency after drying at 65°C is shown for five trenches in Figure 40. A comparison with Figure 35 illustrates that only slight differences occur with the water repellency measured after drying at 25°C.

In conclusion, soil samples from the thatch layer of the treated plot and dried at 65°C, exhibited significantly lower water repellency, when compared with the untreated plot. The persistence of water repellency of the soil samples increased significantly after drying at 105°C at all depths, both for the untreated and treated plot.

3.6. Degree of Potential Water Repellency

The degree of potential water repellency of all samples from the 4 soil blocks was measured using the alcohol test. The relative frequency of the degree of water repellency of samples taken on 25 October 1999 in the untreated and treated plot after drying at 25, 65, and 105°C is shown in Figure 41. Only slight differences in degree occurred between the untreated and treated soil samples from depths of 2.5-19 cm, after drying at 25°C; but a significant difference was established for the
Figure 41 Relative frequency of the degree of potential water repellency of samples (n = 75) dried at 25, 65, and 105°C, respectively, from the untreated and treated 23 October soil blocks.
Figure 42 Relative frequency of the degree of potential water repellency of samples (n = 75) dried at 25, 65, and 105°C, respectively, from the untreated and treated 23 November soil blocks.
Figure 43 Contours of the degree of potential water repellency in horizontal planes (25 cm x 75 cm) at six depths from the untreated and treated 25 October soil blocks. The samples were dried in an oven at 23°C.
Figure 44 Contours of the degree of potential water repellency in five vertical planes (side views) from the untreated and treated 25 October soil blocks. The samples were dried in an oven at 25°C.
Figure 45 Contours of the degree of potential water repellency in horizontal planes (25 cm x 75 cm) at six depths from the untreated and treated 23 November soil blocks. The samples were dried in an oven at 23°C.
Figure 46 Contours of the degree of potential water repellency in five vertical planes (side views) from the untreated and treated 23 November soil blocks. The samples were dried in an oven at 25°C.
Figure 47 Water uptake of soil samples dried at 25°C and taken at depths of 0-2.5 and 2.5-5 cm in the untreated and treated plot between 32 April and 25 October 1999, after 1 and 24 h application of water at the bottom of the samples.
thatch layer at depth of 0-2.5 cm. Nearly all samples from the thatch of the untreated plot needed more than 20% alcohol, whereas most samples from the plot treated with Primer®604 absorbed within 5 s drops with less than 5% alcohol.

Drying at 65°C of the soil samples from all six depths of the untreated and from depths of 2.5-19 cm of the treated plot did not clearly affect the degree of repellency, when compared with drying at 25°C (Fig. 41). However, the degree of repellency of the samples from the thatch layer of the treated plot increased significantly after drying at 65°C. A further drying at 105°C increased significantly the degree for samples from 2.5-12 cm of the untreated plot and for samples from 0-9.5 cm of the treated plot (Fig. 41).

Also the degree of water repellency of samples taken on 23 November in the treated plot from 0-5 cm and dried at 25°C, and from 0-2.5 cm and dried at 65°C was significantly lower in comparison with the untreated plot (Fig. 42). A significant increase in degree occurred after drying at 105°C for samples from depths of 0-12 cm of the untreated and the treated plot. The increase may be influenced by the relatively high organic matter contents at these depths.

The spatial variability of the degree of water repellency after drying the samples at 25°C is shown for six depths of the untreated and treated 25 October plot in Figure 43. Worthy of note is the lower degree at depths of 1.25 and 3.75 cm and the higher degree at depths of 8.25 and 10.75 cm in the treated plot, in comparison with the untreated plot. The variability of the degree in both plots is shown for five side views in Figure 44.

Lower alcohol percentages at depths of 1.25 and 3.75 cm, and relatively higher percentages at depths of 8.25, 10.75, 15.25, and 17.75 cm were found for the treated 23 November soil block in comparison with the untreated block, as is illustrated in Figures 45 and 46.

In conclusion, Primer®604 applications resulted in significantly lower degrees of potential water repellency for samples taken on 25 October and 23 November from the thatch layer, after drying at 25°C and 65°C, when compared with samples from the untreated plot. Drying at 65°C did not clearly affect the degree of repellency, in comparison with 25°C, with the exception of an increase for samples from the treated thatch layer. However, drying at 105°C resulted in a significant increase in degree of potential water repellency for samples taken at depth of 0-12 cm in the untreated as well as the treated plot.

3.7. Resistance to Wetting of Dried Soil Samples

Measurements of the wetting rate of samples dried at 25°C revealed large differences in water uptake between samples taken at same depths, but at different dates. This may be due to differences in initial soil water content and in actual water repellency of the samples in the field at the time of sampling. For example, large differences in water uptake were established during the first hour of wetting between samples taken at depths of 0-2.5 and 2.5-5 cm in the untreated plot on 22 April and 21 September (Fig. 47). The water uptake of samples taken in the thatch layer of the treated plot on 21 September and 12 and 25 October, after several applications of Primer®604, was better in comparison with the untreated plot.
Figure 48 Water uptake of soil samples dried at 25°C and taken at depths of 7.9.5 and 9.5-12 cm in the untreated and treated plot between 22 April and 12 October 1999, after 1 and 24 h application of water at the bottom of the samples.
Figure 49 Water uptake of soil samples dried at 25°C and taken at depths of 14-16.5 and 16.5-19 cm in the untreated and treated plot between 22 April and 12 October 1999, after 1 and 24 h application of water at the bottom of the samples.
Figure 50 Relative frequency of the persistence of actual and potential water repellency of samples from the thatch layer of the untreated and treated plot on several dates.
especially during the first hour of wetting (Fig. 47). Also large differences in water uptake occurred between samples dried at 25°C and taken at depths of 7-19 cm on 22 April compared with those on 12 October (Figs. 48, 49).

4. Discussion and Conclusions

Water repellency of soils may dramatically affect water and solute movement, due to nonuniform wetting and forming of preferential flow paths, so-called fingers, as also often occur in the dune sand studied (Fig. 1). Soil wetting agents have been developed as a possible means for overcoming the problems caused by water repellency (e.g. Letey et al., 1975; Kostka et al., 1997; Ciar 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 in the untreated. However, the applications did not improve the uneven distribution in the soil below the thatch layer. The differences between lowest and highest soil water contents were even larger in the treated plot in comparison with the untreated plot. We assumed that the applications of Primer®604 resulted in a movement of the surfactant from the thatch layer into formed preferential flow paths and thereby inducing a still better wetting of these flow paths. As a consequence, dry pockets in the treated soil were provided with less rainwater and were therefore more persistent when compared with the untreated soil.

A more homogeneous wetting of the treated soil may be realized by using a surfactant that penetrates easily 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 to become water repellent. This is in accordance to the statement of Moore (1981): "Once an areareceiver an effective wetting agent program and has a treated rootzone, surface applied rain and irrigation penetrates rapidly, wets and drains through thatch, and uniformly wets the entire profile."

WDFT results from this experiment suggested that the surfactant was having the greatest effect at the soil surface and in the upper 2.5 cm of the soil profile, the layer with the highest organic matter content. Statistically significant reductions in actual water repellency were established in the thatch layer of the treated plot compared with the untreated plot on 1 June, 2 September, and 21 September 1999 (Fig. 50, upper diagrams). A significant reduction in water repellency was also found for the treated plot at depths of 2.5-5 cm on 2 and 21 September (Figs. 5, 6). There was no significant difference in actual water repellency between the deeper layers of both plots.

Water content has a large effect on the actual water repellency of a soil. The critical soil water content introduced by Dekker and Rissem (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 is introduced here as the "transitional 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 0-2.5 cm and 2.5-5 cm,
as being between soil water contents of 18-23 and 14-19 vol%, respectively. Applications of Primer®604 lowered these transition zones to 12-16.5 and 8-20
vol%, respectively (Figs. 20, 22). This implicates that the surface layer in the
treated soil can dry to lower water contents than in the untreated soil before water
repellency is induced.

The spatial and temporal variability in persistence of potential water
repellency after drying at 25°C was high at depths of 0-2.5 cm in the treated and
untreated plot (Fig. 50). More important, significantly lower WDPT values were
detected for the samples from the Primer treated plot, when compared with the
untreated plot.

Primer®604 applications increased also significantly the wetting rate of the
field-moist samples from the thatch layer (Fig. 32). This may result in a more
effective wetting of the root zone during rain events and artificial supply of water
( irrigation), thereby inducing a better grass growth and a reduction in runoff.

To conclude, regular applications of Primer®604 significantly increased
infiltration rates into the water repellent soil surface. Observed soil water contents
appeared to be higher than found in the untreated plot. Furthermore, the soil water
content range in which water repellency might be induced in the field decreases due
to regular Primer®604 applications.
5. Recommendations

The generally unpredictable response of the WDPT values to drying of wet samples suggests that samples should preferably be taken in a dry status in the field to best reflect the maximum water repellency that can be expected to occur. Numerous researchers did not measure the actual water repellency, but only the potential water repellency after air-drying (e.g. Cisar et al., 2000; Kosíka, 2000) or oven-drying the samples (e.g. Dekker and Jungerius, 1990; Biyom et al., 1993; Hendrickx et al., 1993). King (1981) recommended water repellency tests to be made on oven- or air-dry samples. However, additionally to King (1981) we recommend to measure the actual water repellency on field-moist samples from different depths in the soil profile too, in order to attempt the assessment of the critical soil water contents. Its knowledge aids considerably the identification of the environmental conditions at which the onset of water repellency can be expected for a given soil. This can be of great value for land managers, allowing not only a more effective irrigation of affected soils, by keeping soil water contents above the critical threshold (Dekker 1998), but also the more accurate forecasting of conditions during which increased environmental problems can be expected in relation to water repellency development. These include enhanced hydrological response to rainstorms leading to floods and soil erosion, enhanced leaching of nutrients and agrochemicals, and reduced soil microbial activity.

Water repellent soil and surface layers exhibit a complex flow and transport mechanism. Knowledge of the underlying principles is essential for instance to simulate water availability for crops and to estimate leaching potentials of agrochemicals. We recommend a further study of this test site by combining treatments with sprinkler irrigations to prevent drying of the soil below the critical soil water content, and thereby preventing the soil to become water repellent. Water flow and solute transport processes can be studied by making use of automated TDR measurements and by developing and applying a new modeling approach with incorporation of the preferential flow and transport, for instance in the well-known SWAP model.

We note the uniqueness of this test site as it relates to the extreme depths at which water repellency was found. This is very different from what is normally encountered in golf course soils. Therefore we recommend to carry out a similar study in a golf course soil.
6. References


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