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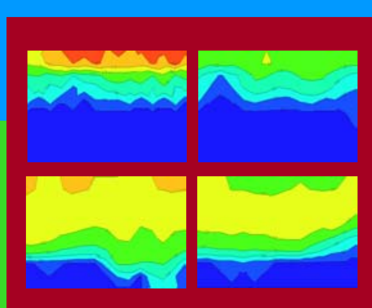

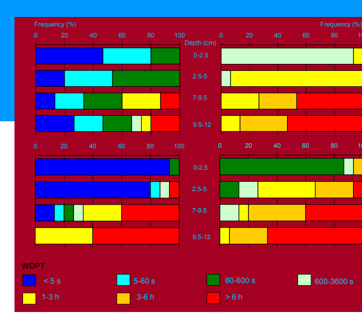

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Influence of surfactant applications on the wettability of a dune sand with grass cover:

Long-term effect of Primer®604 and short-term effect of ACA 1897

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Abstract

Oostindie, K., Dekker, L.W. and C.J. Ritsema, 2003. *Influence of surfactant applications on the wettability of a dune sand with grass cover: Long-term effect of Primer®604 and short-term effect of ACA 1897.* Wageningen, Alterra, Report 659, 54 pp., 27 Figs; 29 References.

This study reports about the effects of surfactant applications in reducing the water repellency of a dune sand with grass cover. In one experiment the effects of former Primer®604 applications in 1999-2001 were studied on the persistence and degree of actual and potential water repellency during dehydration between 11 April and 5 September 2002. Shelters were built on an untreated and former treated plot to protect the soil from wetting by precipitation during this period. At each plot the soil was sampled eight times in transects at depths between 0-33 cm during the dehydration period. Water contents and actual and potential water repellency of the soil samples were measured. The surface layer of the former Primer®604 treated soil was in all eight transects less water repellent, when compared with the untreated soil. Thus, indicating that the effect of surfactant applications is still notable nearly nine months after the last application. In a second experiment effects were studied of the surfactant ACA 1897 on the wetting and persistence and degree of the actual and potential water repellency of the topsoil. This surfactant was applied 18 times at a rate of 0.2 ml/m^2 between 5 June and 2 October 2002. Soil samples and soil columns were taken after 6, 12, and 18 applications. The persistence of actual and potential water repellency of the soil samples from the treated plot were found to be significantly lower at depths of 0-2.5 cm and 2.5-5 cm, after 12 and 18 applications of ACA1897, when compared with the untreated plot.

Keywords: water repellency, critical soil water content, surfactant

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Contents

Summary

Dry soils are normally easily wetted by rainfall and irrigation. However, some soils resist wetting and are considered to be water repellent and to exhibit hydrophobic properties. The problem of soil water repellency has been recognized in sand, loam, clay and peat soils in various parts of the world and is common and most pronounced in sandy soils supporting turf or pasture grasses.

Water repellency is influenced by season and soil water content. In most cases, repellency is most severe during summer and decreases or disappears during the winter months. Water repellency may dramatically affect water and solute movement and has been shown to cause decreased infiltration of irrigation water and precipitaton, non-uniform wetting of soil profiles, and leaching due to preferential flow.

Soil wetting agents have been developed as a possible means for overcoming the problems caused by water repellent soils. Surfactants are well documented for the management of water repellency in thatch and surface layers in sandy soils and for the enhancement of soil hydration in managed turfgrass.

Slightly water repellent and wettable dune sand with grass cover were found to be altered into extremely water repellent soil within one week of dehydration under shelters. The most extreme water repellency, with water drop penetration times of more than six hours, were detected in large parts of transects sampled in the untreated and former Primer®604 treated plot between 11 July and 5 September 2002.

It is striking that the surface layer of the former Primer®604 treated soil was always less water repellent in comparison with the untreated soil. Thus, the effect of surfactant applications is still notable nearly nine months after the last application.

In general, slightly lower alcohol percentages have been detected in the transects of the Primer®604 treated soil, when compared with the untreated soil. Thus, indicating a lower degree of actual water repellency.

The dehydration process decreased the water contents and increased the persistence of actual water repellency in most layers of the untreated and former Primer®604 treated soil, but decreased the degree (as measured by the alcohol percentage test) of actual water repellency, especially in the former Primer treated plot. Thus, the severity of the persistence of the actual water repellency of the dune sand studied, measured with the WDPT test, does not go hand in hand with the severity of the degree, as measured by the alcohol percentage test.

The persistence of potential water repellency of the six transects sampled in April was less extreme, when compared with the transects sampled between 15 May and 5 September. These differences are supposed to be the result of the higher soil water contents and the lower severity of the actual water repellency in the April transects, in comparison with the transects sampled later. Noteworthy is also the lower severity of the persistence of potential water repellency in the surface layer of the Primer®604 treated plot, and the greater difference in severity with the underlying soil, when compared with the untreated plot.

The persistence or stability of potential water repellency of the untreated and former Primer®604 treated soil considered in relation to its degree increased with

depth. The tendency of this persistence/degree ratio to increase with depth is undoubtedly related with the characteristic and content of the organic matter.

The surfactant ACA 1897 was applied 18 times at a rate of 0.2 ml/m^2 between 5 June and 2 October 2002. Significantly lower values for the persistence of actual and potential soil water repellency were detected at 0-2.5 cm and 2.5-5 cm depth, after 12 and after 18 applications in the ACA treated plot, when compared with the untreated plot.

The measurements of the degree of actual and potential water repellency on samples from the untreated and ACA treated plot gave remarkable results. Extremely high alcohol percentages, often exceeding 27.5%, were detected for the field-moist samples in both plots on 30 August and 8 October 2002. However, drying of these samples decreased the severity. This implicates that the use of the alcohol percentage test on the field-moist samples overestimates the degree of soil water repellency.

1. Introduction

Dry soils are normally easily wetted by rainfall and irrigation. If the attractive forces are neutralized or absent, e.g. because of the presence of a hydrophobic coating on sand grains or aggregates, soils are said to resist wetting and are considered to be water repellent and to exhibit hydrophobic properties. A water repellent soil will be defined as one which does not wet spontaneously when a drop of water is placed upon the surface. Water repellency has been observed in sand, loam, clay, and peat soils all over the world (Wallis and Horne, 1992; Dekker and Ritsema, 2000; Jaramillo et al., 2000; Feng et al., 2002). However, the phenomenon is most pronounced in course textured soils and is common in sandy soils supporting turf or pasture grasses.

Although water repellent soil has several possible causes, numerous researchers agree that an organic coating on the soil particles causes the problem. This coating does not necessarily cover the soil particles completely nor is it always very thick. A thin and/or partial covering of the soil particles can render them water repellent (Bisdom et al., 1993). However, mineral particles need not be individually coated with hydrophobic material; 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).

Water repellency is influenced by season and soil water content. In most cases, repellency decreases during the winter months and is most severe during summer. This seasonal variation may be due to soil moisture conditions. Long, hot, dry periods are helping to produce the formation of water repellent soils. Likewise, extremely wet weather can lessen or even eliminate water repellency for several weeks. There appears to be a critical soil water content for each water repellent soil layer, below which the soil is water repellent and above which the soil is wettable (Dekker and Ritsema, 1994).

Water repellency may dramatically affect water and solute movement at the field-scale, a process which has often been underestimated (Bauters et al., 2000). Water repellency and its spatial variability have been shown to cause decreased infiltration of irrigation water and precipitation, non-uniform wetting of soil profiles, increased runoff, and leaching due to preferential flow (Ritsema et al.,1997,Dekker et al., 2001a,b).

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; Kostka et al., 1997; Kostka, 2000). Surfactants are well documented for the management of water repellency in thatch and surface layers in sandy soils and for the enhancement of soil hydration in managed turfgrass (Miller and Kostka, 1998; Karnok and Tucker, 2001; Kostka et al., 2002; Dekker et al., 2003a,b).

Maintenance of turf quality and simultaneous optimization of irrigation and conservation of water are goals of turfgrass managers, especially under drought conditions. Water may be conserved by maximizing the effectiveness of irrigation and precipitation or by minimizing the losses of transpiration, evaporation, and leaching or drainage below the rootzone.

Dekker et al. (2000b) studied the effectiveness of the surfactant Primer®604 for amelioration and management of soil water repellency in a dune sand with grass cover near the village of Ouddorp, in the southwestern part of the Netherlands during the period 22 April to 23 November 1999. During that period the surfactant was applied twelve times at a rate of 1.85 ml per square m. Soil samples were taken at six depths in trenches in the treated and untreated plot over a seven-month period. 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 were found for the surface layer of the treated plot. 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 introduced.

In the same experimental field, effects of Primer®604 applications and water irrigations on the wetting and severity of water repellency were studied by Oostindie et al. (2002) during the summer periods of 2000 and 2001. During 2000 the surfactant was applied thirteen times and during 2001 nineteen times at a rate of 1.85 ml per square meter. Applications of Primer®604 as well as irrigations were found to lower the persistence of actual water repellency in the surface layer (0-5 cm). The combination of irrigations and surfactant applications was most effective in beating the water repellency phenomenon.

In the present study the same field has been used for two experiments. In the first experiment effects of the Primer®604 applications in 1999, 2000, and 2001 on the persistence and degree of actual and potential water repellency were studied during dehydration of the grasscovered sandy soil in the untreated and former treated plot between 11 April and 5 September 2002. Shelters were built on the plots to protect the soil from wetting by precipitation during this period. In the second experiment effects were studied of the surfactant ACA 1897 on the wetting and persistence and degree of the actual and potential water repellency of the topsoil. This experiment was performed in the untreated soil plot from former studies in this field. ACA 1897 was applied 18 times at a rate of 0.2 ml/m^2 between 5 June and 2 October 2002.

2. Materials and Methods

2.1. Field-soil

The experimental field is located on a dune sand near Ouddorp, in the south-western part of the Netherlands. The soil consists of fine sand with less than 3% clay to a depth of more than 3 m and is classified as Typic Psammaquent (Dekker, 1998). The site is a grass-covered pasture and has not been tilled for at least several decades. An organic matter content of 12.5 w% was established in the surface layer (0-2.5 cm) and of 9.5 w% in the second layer (2.5-5 cm). At depths of 7-9.5 cm an organic matter content was detected of 4.8 w% and at depths of 9.5-12 cm of 2.4 w%. It further decreased to 1.5 w% at depth of 14-16.5 cm and 1.1 w% at depths of 16.5-19 cm. Below this depth the organic matter content was found to be around 0.5 w%.

The soil studied can 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).

Figure 1 Shelters being built for the dehydration experiment.

2.2. Treatments and Soil Sampling

Between 22 April 1999 and 18 December 2001 the wetting agent Primer®604 (Aquatrols, Cherry Hill, New Jersey, U.S.A) was applied, in total 44 times, to a part of the experimental field (25 m by 5 m) at a rate of 1.85 ml/m^2 with a volume solution of 70 ml/m^2 with a Mesto Pico backpack-type sprayer (Dekker et al., 2000b; Oostindie et al., 2002). An adjacent same area was not treated and was used for comparison.

During the period 11 April to 5 September 2002 the effects of the former Primer®604 applications on the development of persistence and degree of actual and potential water repellency were studied during dehydration of the soil. Shelters were built on a part of the untreated plot and former treated plot to protect the soil profiles from wetting by precipitation (Fig. 1).

Soil samples were taken at eight depths in vertical transects under both shelters on 11, 19, 25 April, 1, 15 May, 4 June, 11 July, and on 5 September 2002 to study the persistence and degree of the actual and potential water repellency during the drying process. The soil was sampled at depths of 0-2.5, 2.5-5, 7-9.5, 9.5-12, 14-16.5, 16.5-19, 21-26, and 28-33 cm, using steel cylinders with a diameter of 5 cm. At each depth 15 samples were taken in close order over a distance of about 75 cm. 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 and the persistence and degree of actual water repellency were measured. All samples had been oven-dried at 65^0C and weighed to calculate the soil water content.

The surfactant ACA 1897 was applied at a rate of 0.2 ml/m^2 on a part (3m by 3m) of the untreated plot used in former experiments (Dekker et al., 2000b; Oostindie et al., 2002). To compare and study the effects of the surfactant on the persistence and degree of actual and potential soil water repellency an adjacent plot with the same area was not treated. The surfactant was applied almost weekly, and in total 18 times, between 5 June and 2 October 2002. The treated plot as well as the untreated plot were irrigated after the applications. Between 5 June and 31 July 9 times 10 mm, on 9 and on 20 August 5 mm, and from 26 August to 2 October each time 2.5 mm of water was irrigated.

The soil in the two plots was sampled for soil water content and soil water repellency measurements on 17 July, 30 August and 8 October 2002, after respectively 6, 12, and 18 treatments and irrigations. In these six transects 15 samples were taken at four depths (0-2.5, 2.5-5, 7-9.5, and 9.5-12 cm) over a horizontal distance of around 75 cm. Persistence and degree of water repellency were measured on the field-moist samples and after drying these samples at 65^oC.

Additionally soil columns, including grass cover were carved out, using steel cylinders with a height and diameter of 20 cm, in the treated and untreated plot after six, twelve and eighteen applications of ACA 1897. These columns were allowed to dehydrate during at least two months, before they were sampled in threefold with steel cylinders with a diameter of 5 cm at depths of 0-2.5, 2.5-5, 7-9.5, 9.5-12, 14-16.5, and 16.5-19 cm. Persistence and degree of soil water repellency were measured immediately after sampling, thus indicating the actual water repellency under dry conditions, and after drying the samples at 65^0C.

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. We measured the water repellency of the soil samples under controlled conditions at a constant temperature of 20^0C and a relative air humidity of 50%. In general, a soil is considered to be water repellent 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 upon the time needed for the water drops to penetrate into the soil: class 0, wettable, non-water repellent (infiltration within 5 s); class 1, slightly water repellent (5 to 60 s); class 2, strongly water repellent (60 to 600 s); class 3, severely water repellent (600 s to 1 h); and extremely water repellent (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 samples from the dehydrated soil columns, the so-called "actual soil water repellency", and of the samples after drying in an oven, the so-called "potential soil water repellency" (Dekker and Ritsema, 1994). Measurements of the actual water repellency were performed immediately after assessment of the wet weights of the samples. The persistence of potential water repellency of the samples were measured after drying at 65^0C. The WDPT tests were deferred for at least 2 days to obtain samples in equilibrium with the ambient air humidity (Doerr et al., 2002).

2.4. Alcohol Percentage Test

Over the years many techniques have been developed to measure soil water repellency (King, 1981; DeBano, 2000). One of the simplest and most common methods of classifying water repellency is the (WDPT) test, as described before. Another common used 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 the samples taken in the transects and in the dehydrated soil columns, 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 field-moist samples and on the dried samples under controlled conditions at a constant temperature of 20^0C and a relative air humidity of 50%. The degree of potential water repellency was measured after drying the samples at 65^0C and allowing them to equilibrate with the ambient air humidity during at least two days.

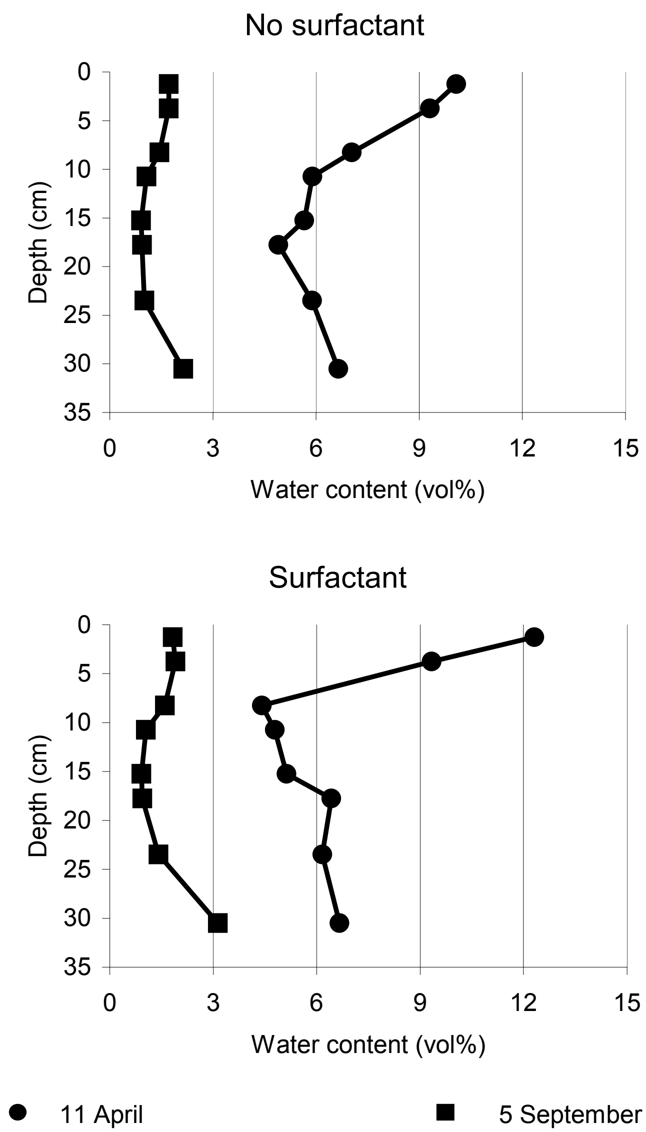

Figure 2 Mean soil water contents at eight depths (n = 15) in the untreated plot and in the former Primer®604 treated plot on 11 April at the start and on 5 September 2002 at the end of the dehydration experiment.

3. Results

3.1. Long-term Effect of Primer®604

3.1.1. Soil Water Contents During Dehydration

The mean volumetric soil water contents, measured at eight depths in the untreated and former Primer®604 treated plot, varied between 4 and 12.5% at the start of the hydration experiment on 11 April 2002 (Fig. 2). At the end of the dehydration process the grass cover was brown and the soil profiles dried to water contents between 1 and 3 vol% (Fig. 2).

The amounts of water in eight soil layers of the untreated and former Primer(®604 treated plot during dehydration have been expressed in mm water. These amounts have been depicted for the eight sampling dates in Figure 3. The surface layers between 0 and 6 cm depths at both plots became regularly drier between 11 April and 4 June 2002. A regular decrease in water amount in the soil profile to 33 cm depth was found in the former Primer®604 treated plot between 11 April and 5 September. Drying of the upper 33 cm in the untreated plot was less regular with a jump to lower water amounts between 11 and 19 April and also between 15 May and 4 June (Fig. 3). The small increase in water amount in some soil layers in both plots on 1 May, maybe due to some lateral inflow through the layers from outside the sheltered soil.

The spatial distributions of the soil water content in the untreated and former Primer®604 treated soil profiles during the period of dehydration have been depicted in the contour plots of Figure 4. As shown in the pictures, only slight differences in soil water content occurred between the two sites on any sampling date.

3.1.2. Actual Soil Water Repellency

The development of the persistence of water repellency during dehydration in the field under the shelters is illustrated in Figure 5. It is noteworthy, that within one week of drying, slightly water repellent and wettable soil could be altered into extremely water repellent soil, as can be seen in comparing the contour plots of 11 April with those of 19 April. Extreme water repellency was established in parts of all transects, sampled between 19 April and 5 September. At both sites the most extreme water repellency, with WDPT values exceeding six hours, was found in large parts of the transects from 11 July and 5 September. It is striking that the surface layer of the former Primer®604 treated soil was always less water repellent in comparison with the untreated soil. Thus, the effect of surfactant applications is still notable nearly nine months after the last application (see for instance the contour plots of 5 September).

The development of the degree of water repellency during the dehydration in the field sheltered, has been illustrated by the contour plots of Figure 6. In general, slightly lower alcohol percentages had been detected in the transects of the former Primer®604 treated soil, when compared with the untreated soil.

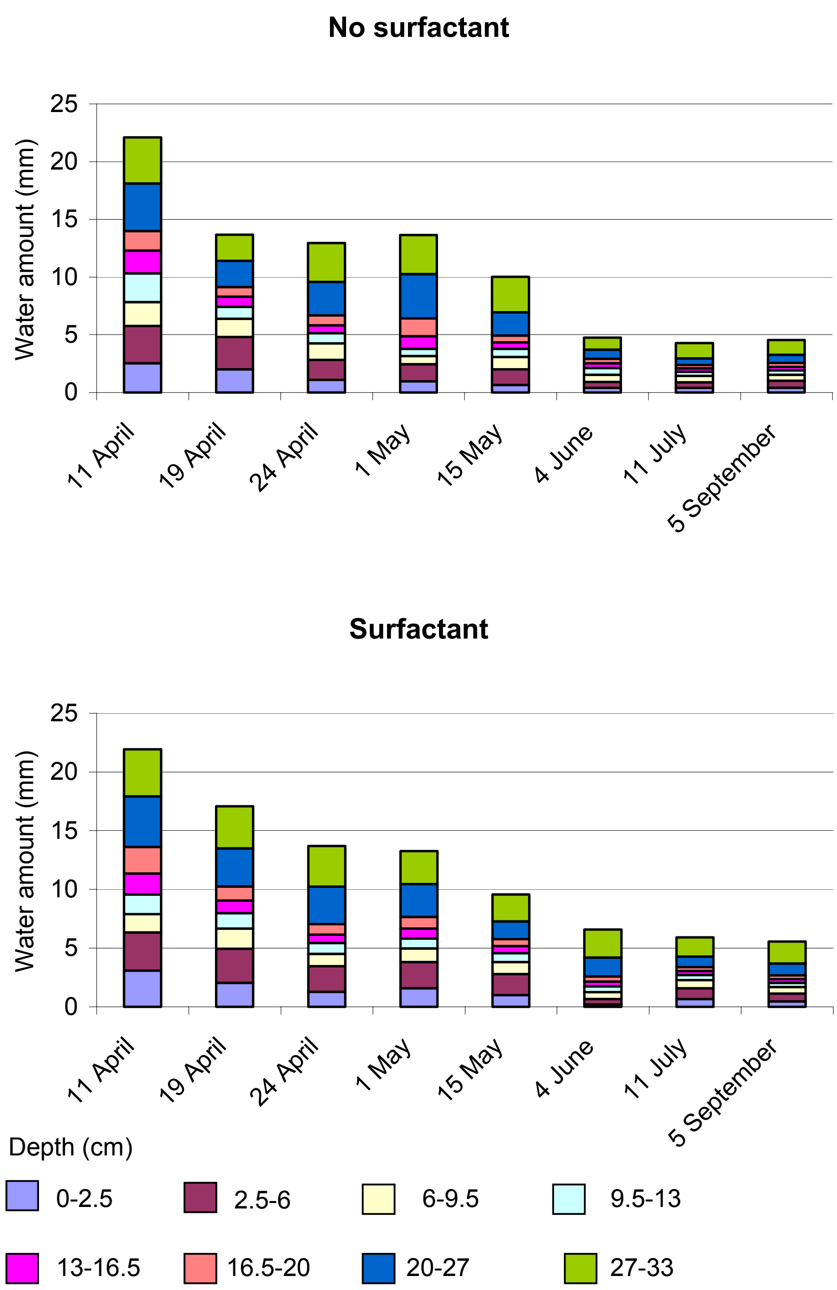

Figure 3 Mean amounts of water in 8 layers of the soil profiles (n = 15) between 0 and 33 cm depth on 8 days between 11 April and 5 September 2002.

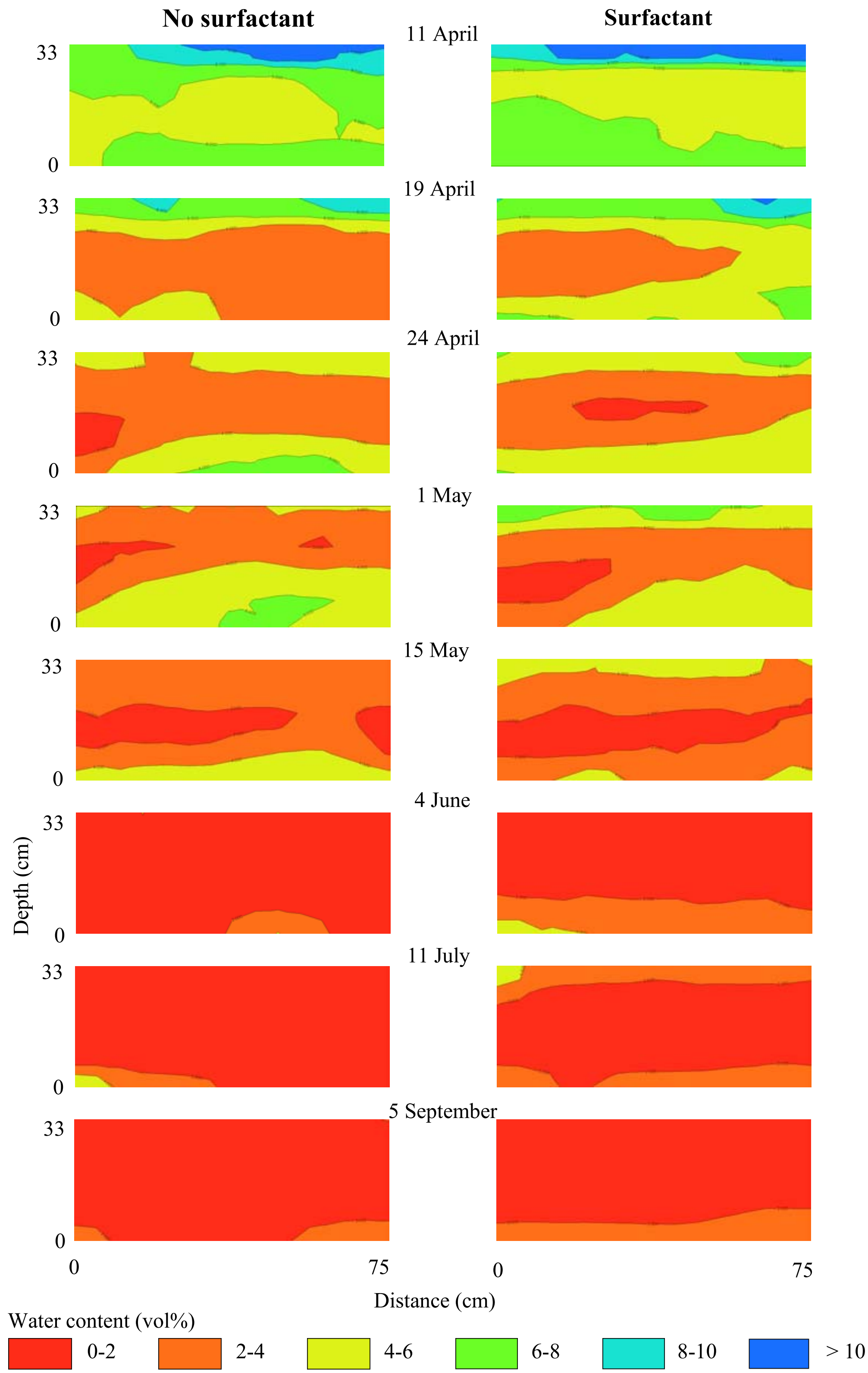

Figure 4 Contour plots (width 75 cm; depth 33 cm) of the soil water content at the two sites between 11 April and 5 September 2002.

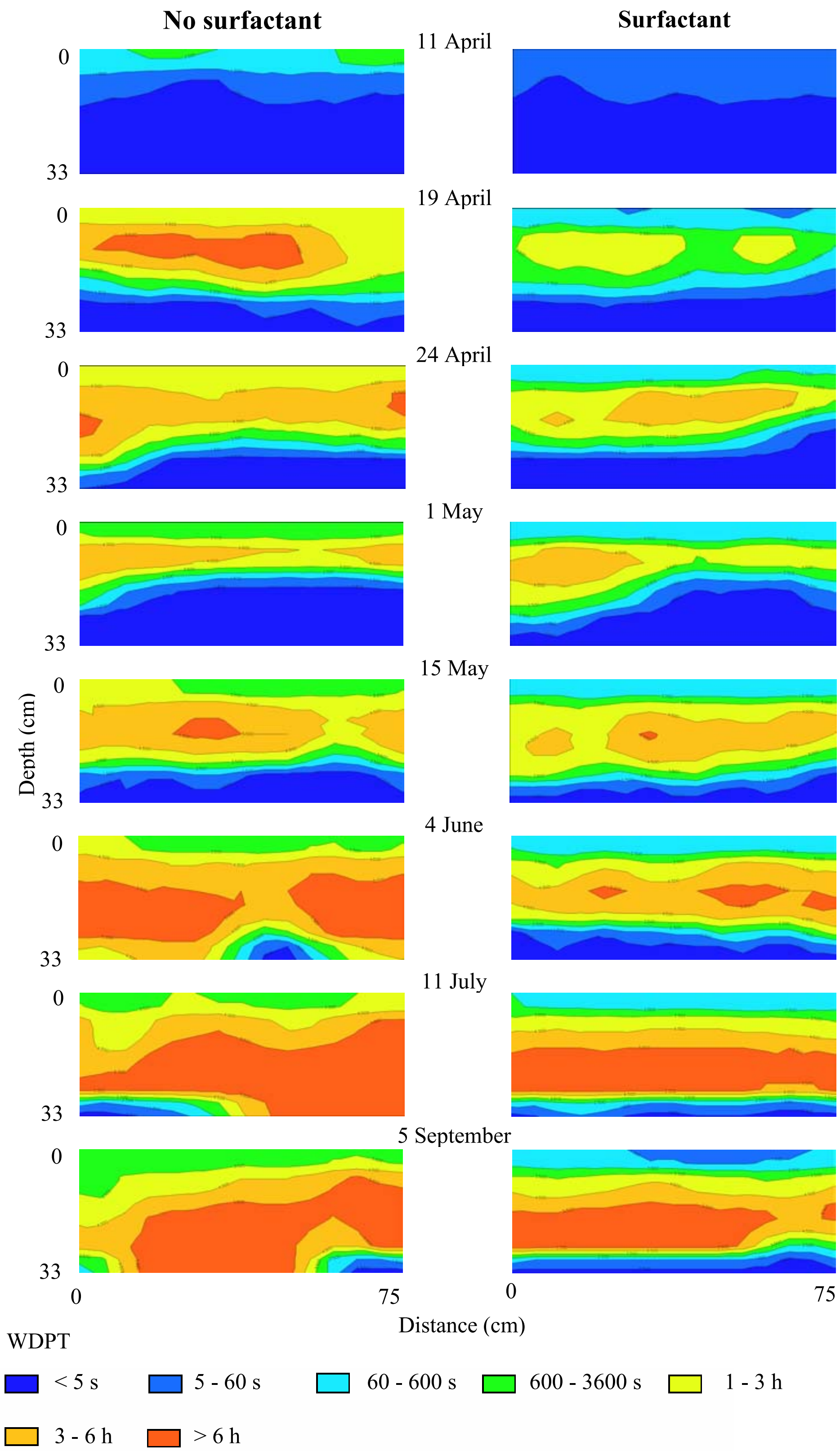

Figure 5 Contour plots (width 75 cm; depth 33 cm) of the persistence of actual soil water repellency at the two sites between 11 April and 5 September 2002.

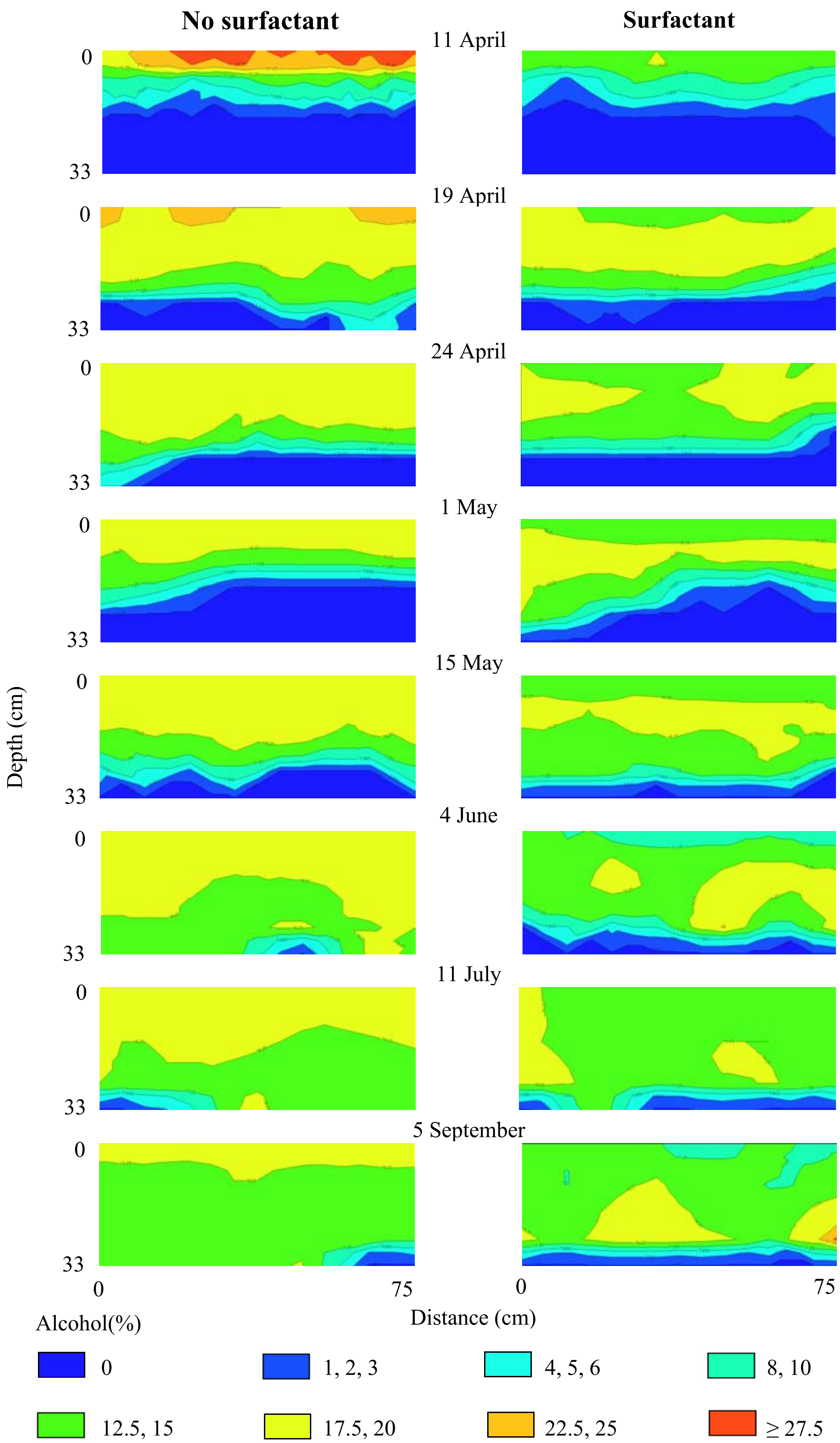

Figure 6 Contour plots (width 75 cm; depth 33 cm) of the degree of actual soil water repellency at the two sites between 11 April and 5 September 2002.

It is remarkable, that in the untreated soil the highest alcohol percentages were detected in the still moist surface layer of the 11 April transect (Fig. 6). This in contrast to the lower WDPT values found in this layer, as shown in the concerning contour plot in Figure 5. Relatively high alcohol percentages were also measured for a part of samples from the surface layer of the 19 April transect (Fig. 6).

The severity of the persistence of actual water repellency was significant lower at depths between 0-12 cm in the former Primer®604 treated plot on 11, 19, 24 April and 1 May, when compared with the untreated soil, as is shown in Figure 7. Large parts of the soil profile with extreme repellency were detected in the transects of 19 and 24 April in the untreated plot (Fig. 7).

Figure 8 shows that extreme water repellency with WDPT values of more than 6 h developed in large parts of both soil profiles at depths greater than 9.5 cm between 15 May and 5 September. Figure 8 also shows that in the surface layer at 0-5 cm depth, the persistence of water repellency was significantly lower in the former Primer®604 treated plot than in the untreated plot on these four sampling dates.

The alcohol percentage test performed on the field-moist samples taken in the transects of April and on 1 May showed a significant lower degree of water repellency in the surface layer at 0-5 cm depth in the former Primer®604 treated plot in comparison with the untreated plot (Fig. 9). Extremely high alcohol percentages of more than 27.5% have been detected at depths of 0-2.5, 2.5-5, and 7-9.5 cm in the untreated plot and at 7-9.5 cm depth in the former Primer®604 treated plot on 11 April (Fig. 9). Thus, suggesting an extreme degree of water repellency, whereas in contrast with the WDPT test for these samples only strong to severe persistence had been measured, as shown in Figure 7.

The degree of actual water repellency, as measured by the alcohol percentage test, increased in the deeper soil layers sampled in the untreated plot between 15 May and 5 September 2002, but remained equal or decreased a bit in the upper layers (Fig. 10). An extreme decrease in degree of actual water repellency occurred in a large part of the profile in the former Primer®604 treated soil between 15 May and 5 September (Fig. 10).

Noteworthy are also the significantly lower alcohol percentages in the four transects sampled between 15 May and 5 September in the former Primer®604 treated plot, in comparison with the untreated plot, as illustrated in Figure 10.

To conclude: the dehydration process decreased the water contents and increased the persistence of actual water repellency in most layers of both soils, but decreased the degree (as measured by the alcohol percentage test) of actual water repellency, especially in the former Primer®604 treated plot.

3.1.3. Relationship Between Soil Water Content and Actual Water Repellency

The relationships between soil water content and WDPT and between soil water content and alcohol percentage of all field-moist samples, taken in the transects of the untreated and Primer®604 treated plot between 11 April and 5 September 2002, have been depicted in Figures 11 and 13, and Figures 12 and 14, respectively, for the four upper and for the four deeper soil layers.

Figure 11 shows that in the untreated plot at 0-2.5 and 2.5-5 cm depth over a wide range of soil water contents WDPT class 2 (60-600 s) class 3 (600-3600 s), as well as class 4 (1-3 h) occurred. Alcohol percentages of these samples, on the other hand, increased from 17.5-20% at lower to 30% at higher soil water contents. Figure 11 also shows that at 9.5-12 cm depth soil samples with water contents of less than 5 vol% exhibited extreme water repellency with WDPT values of 1 to more than 6 hours (classes 4-6), whereas soil samples with water contents between 5-10 vol% were slightly to strongly repellent (WDPT class 1-2). It is also noteworthy that the alcohol percentages of these wetter (5-10 vol%) samples varied enormously, with percentages between 1 and 30%.

Figure 12 shows that in the former Primer®604 treated plot at 0-2.5 cm depth over a wide range of soil water contents WDPT class 1 and 2 and at 2.5-5 cm WDPT class 1, 2 and 3 occurred, thus significantly lower than in the untreated plot (Fig. 11). Also alcohol percentages were found to be evidently lower at both depths in the former treated plot, when compared with the untreated plot. It is remarkable that at 9.5-12 cm depth in the former treated plot soil samples with water contents between 4 and 6 vol% were wettable (class 0) or slightly water repellent (class 1) on 11 April, but strongly (class 2) to extremely repellent (class 4) on 18 and 24 April. Alcohol percentages measured on the samples with a soil water content of 4-6 vol%, varied between 0-10% on 11 April, and between 17.5-22.5% on 19 and 24 April.

The persistence of actual water repellency tends to increase with lower soil water contents at depths between 16.5 and 33 cm in both plots (Figs. 13 and 14). However, alcohol percentages tend to decrease with lower soil water contents, but they drop on the other hand, within a small range at higher soil water contents (Figs. 13 and 14).

3.1.4. Relationship Between Persistence and Degree of Actual Water Repellency

The relationship between the severity of the persistence of actual soil water repellency, measured with the WDPT test, and the severity of the degree, measured with the alcohol percentage test, have been depicted in Table 1 for the 960 samples taken in the untreated plot, and in Table 2 for those of the former Primer®604 treated plot.

The relationship between WDPT class and alcohol percentage of the field-moist samples is very bad. For instance WDPT class 1 corresponds with alcohol percentages in the range from 1 to 25% in the untreated (Table 1) and from 1 to 20% in the former treated plot (Table 2). However, also the persistence of extreme actual water repellency (WDPT class 6) of samples corresponds with alcohol percentages in the range from 12.5 to 22.5% in the untreated and from 10 to 20% in the former treated plot.

In conclusion: the severity of the persistence of the actual water repellency of the soil studied, measured with the WDPT test, does not go hand in hand with the severity of the degree of the actual water repellency, as measured by the alcohol percentage test.

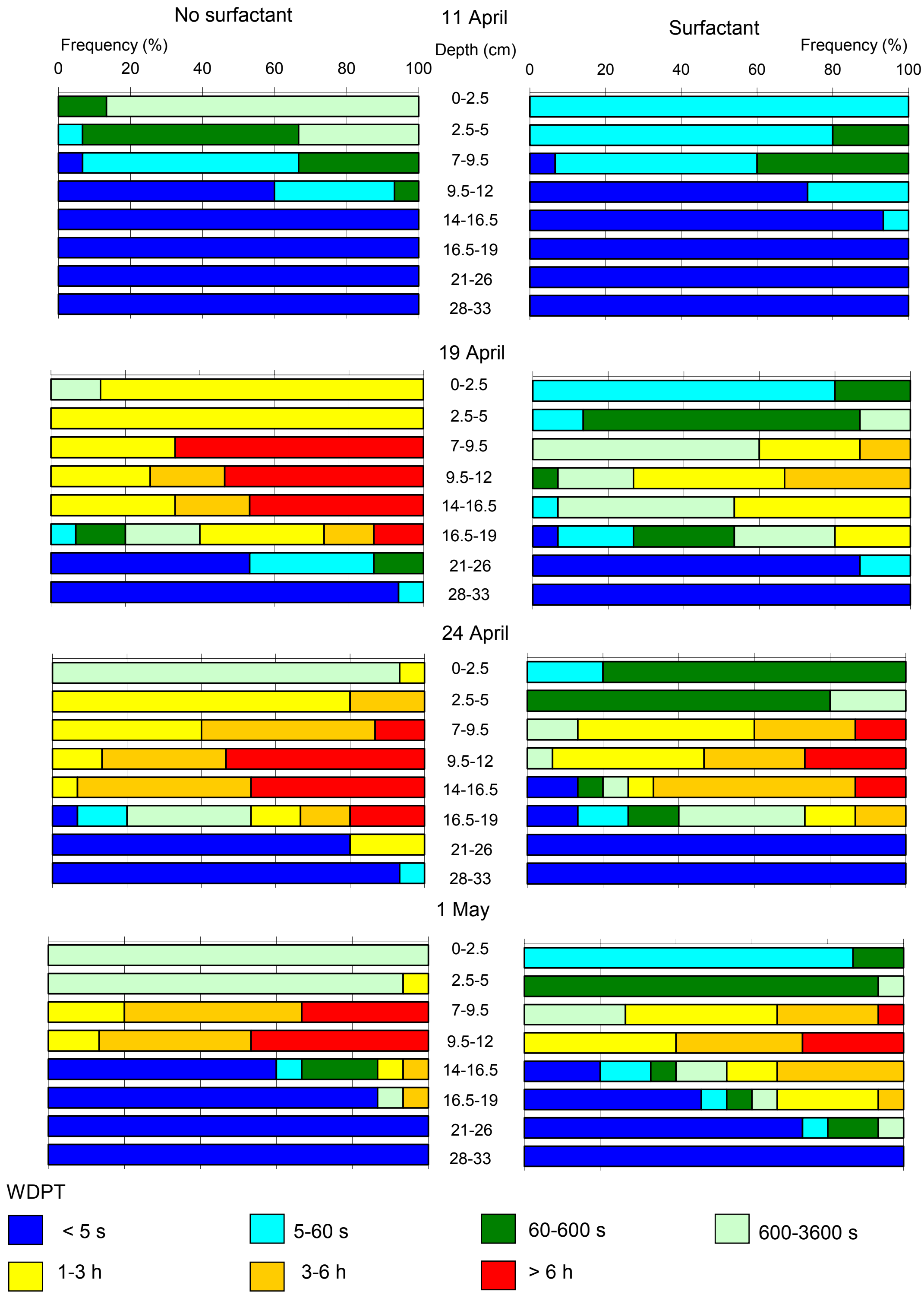

Figure 7 Relative frequency of the persistence of actual water repellency of soil samples, taken between 11 April and 1 May 2002 at 8 depths, in the untreated and in the former Primer®604 treated plot (n = 15).

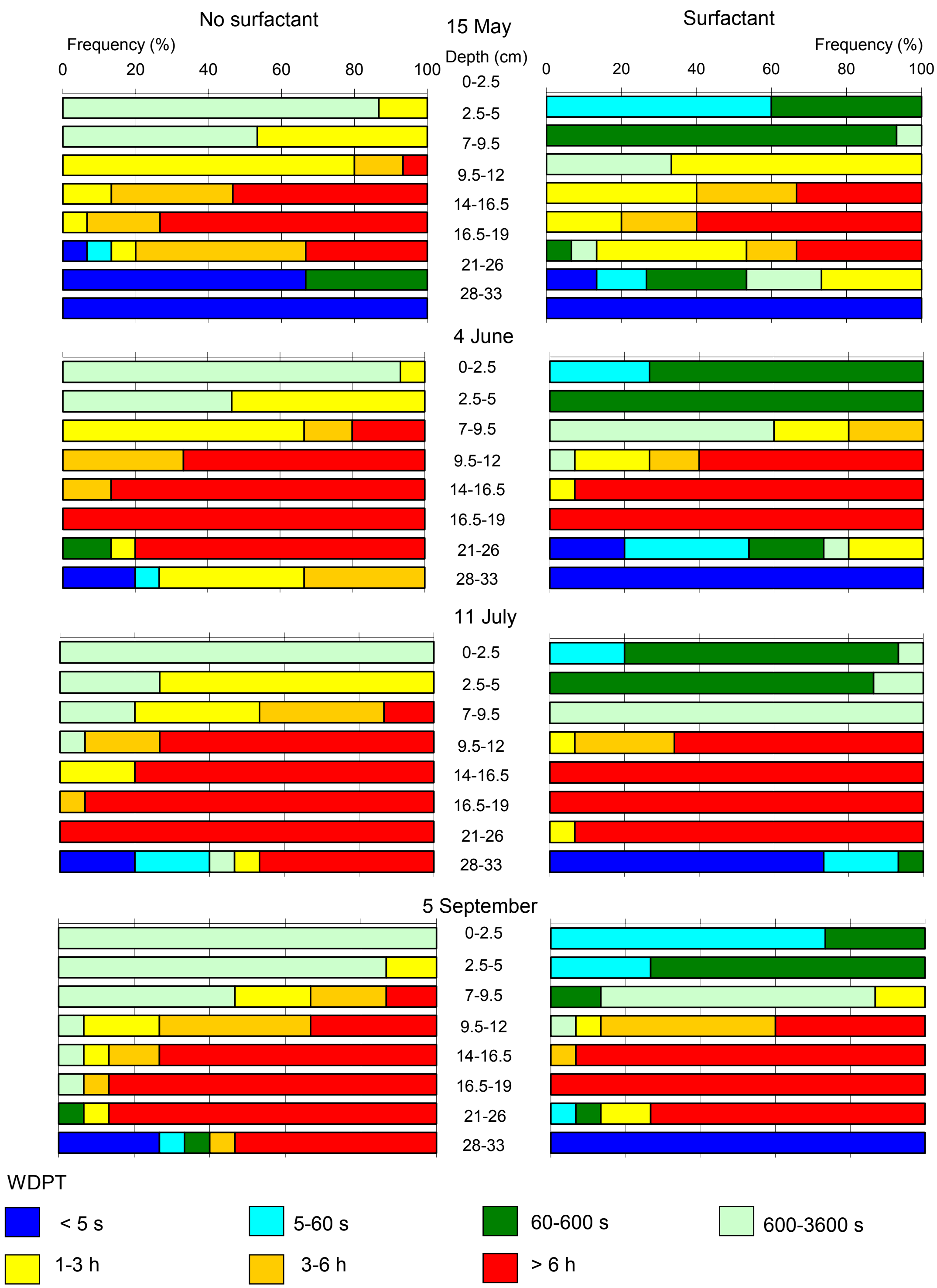

Figure 8 Relative frequency of the persistence of actual water repellency of soil samples, taken between 15 May and 5 September 2002 at 8 depths, in the untreated and in the former Primer®604 treated plot (n = 15).

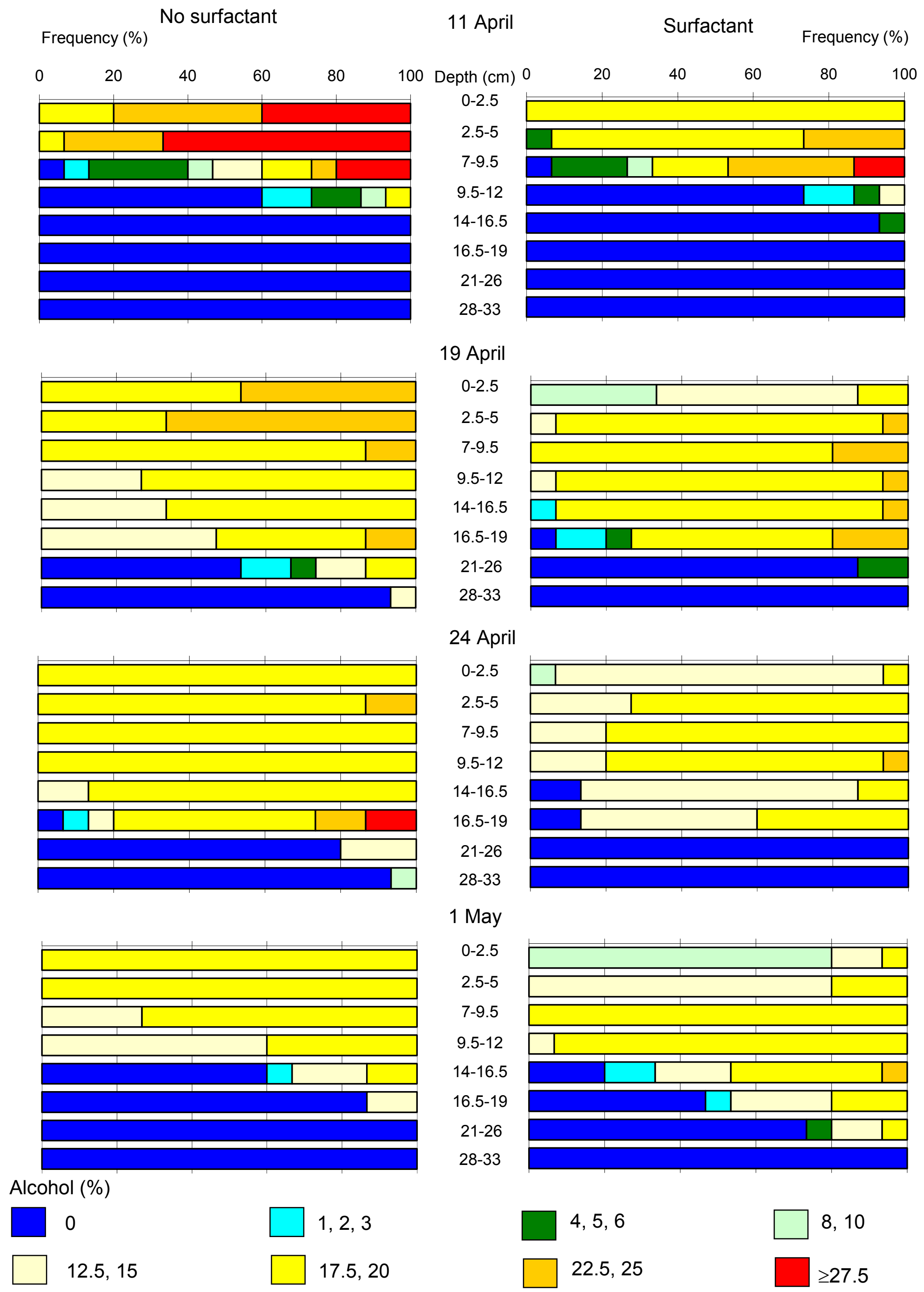

Figure 9 Relative frequency of the degree of actual water repellency of soil samples, taken between 11 April and 1 May 2002 at 8 depths, in the untreated and in the former Primer®604 treated plot (n = 15).

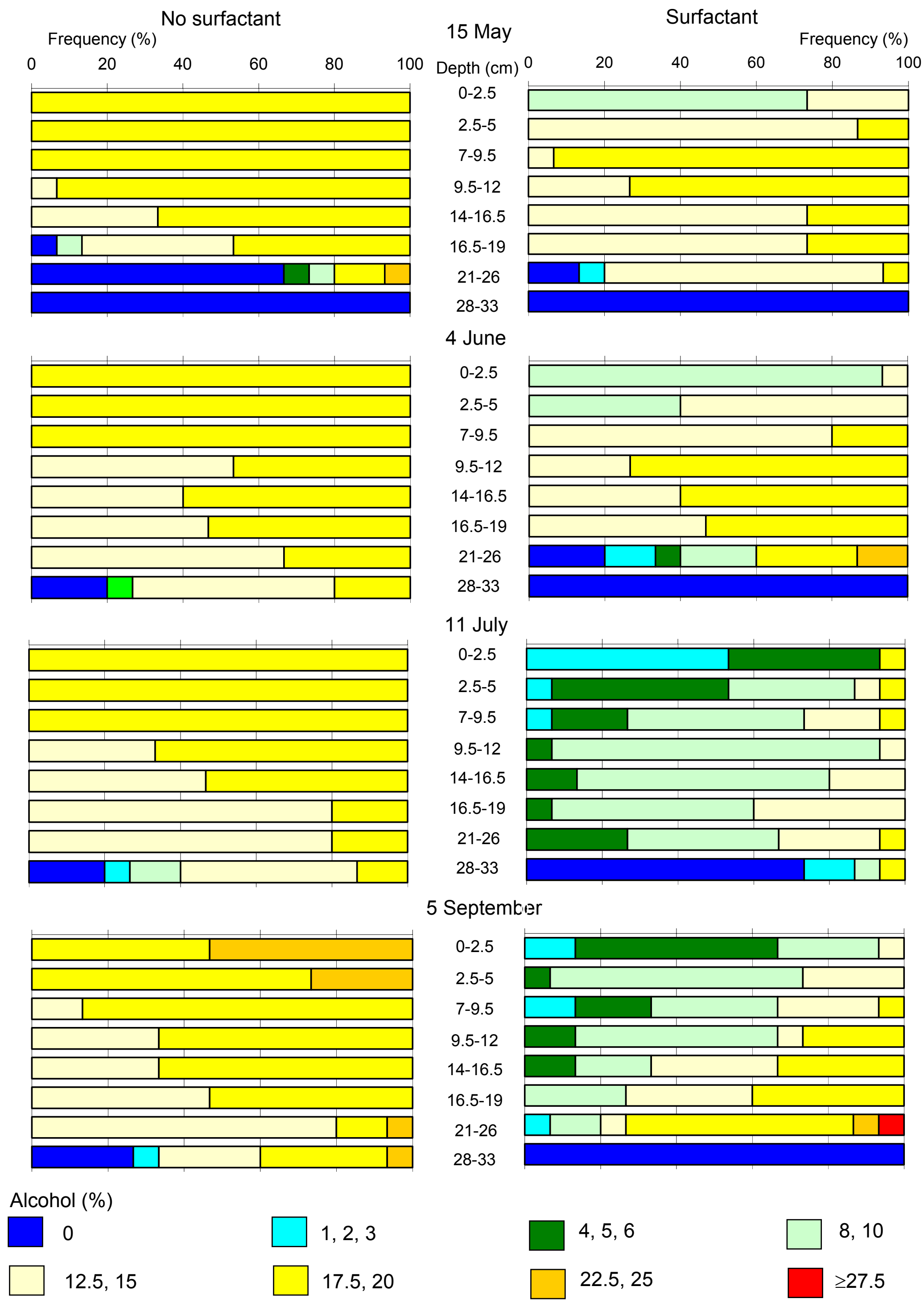

Figure 10 Relative frequency of the degree of actual water repellency of soil samples, taken between 15 May and 5 September 2002 at 8 depths, in the untreated and in the former Primer®604 treated plot (n = 15).

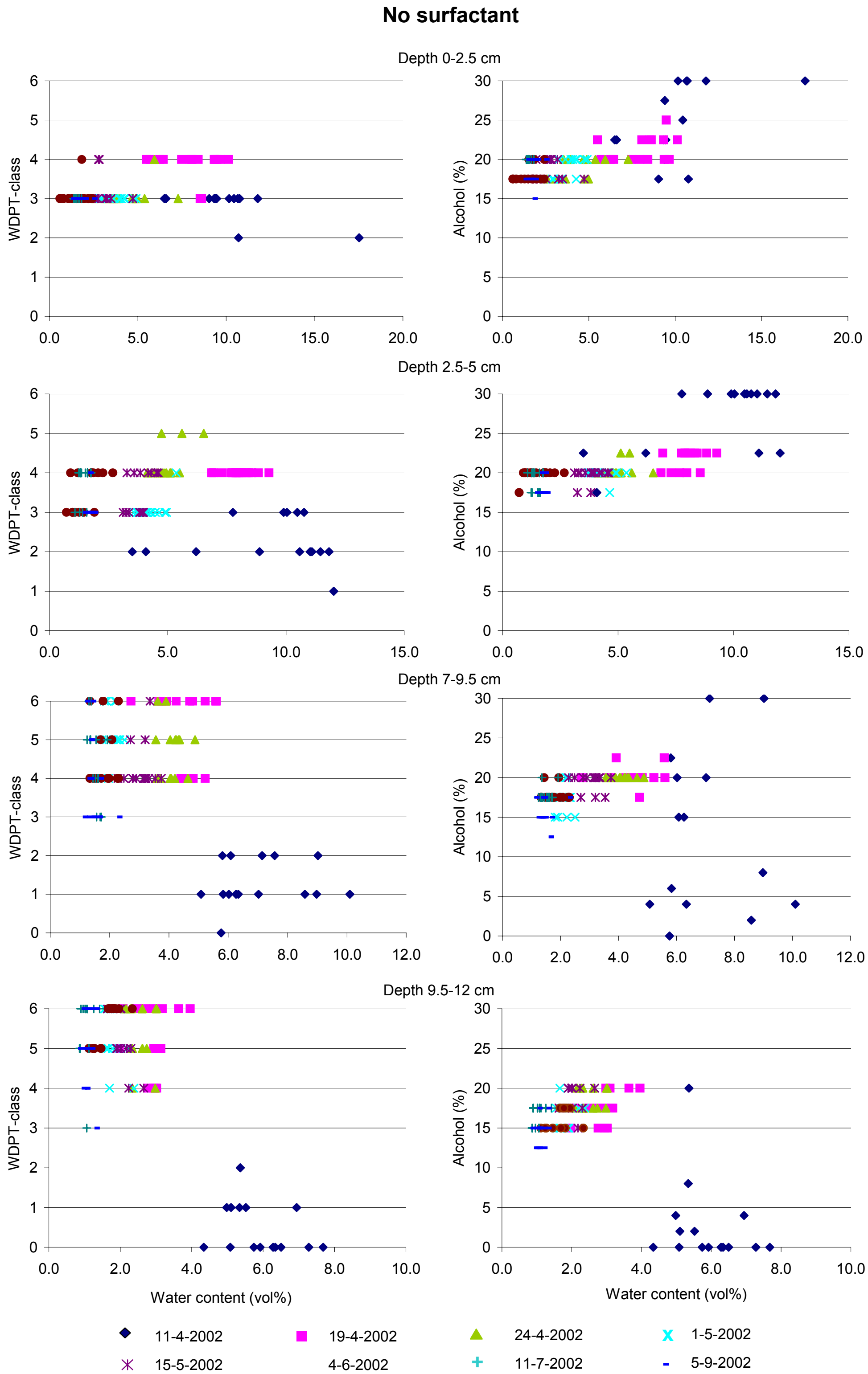

Figure 11 Relationships between soil water content and water repellency (WDPT class and Alcohol %) of the field-moist samples taken at four depths in the untreated plot on eight, separately indicated, sampling dates (n = 120).

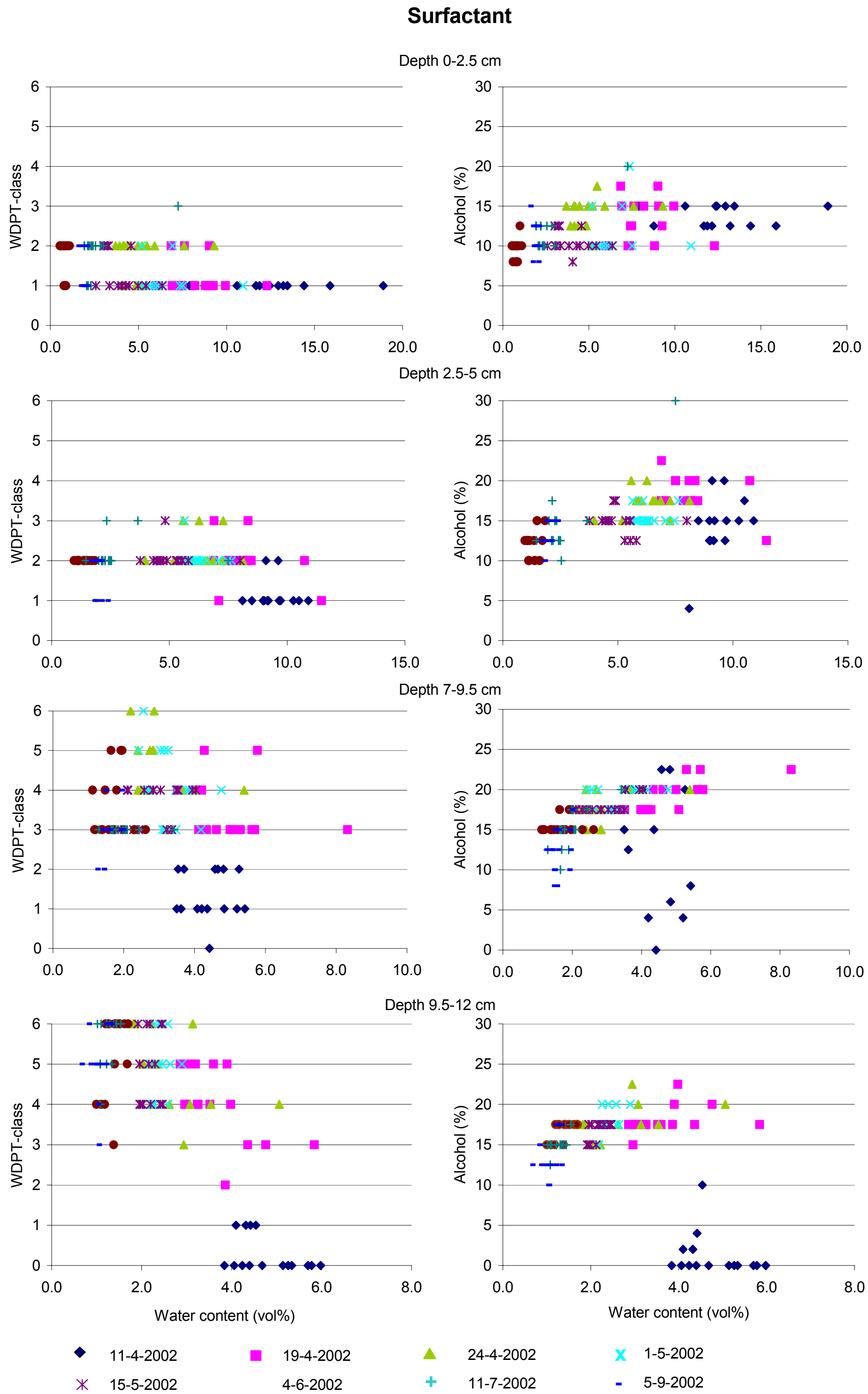

Figure 12 Relationships between soil water content and water repellency (WDPT class and Alcohol %) of the field-moist samples taken at four depths in the former Primer®604 treated plot on eight, separately indicated, sampling dates (n = 120).

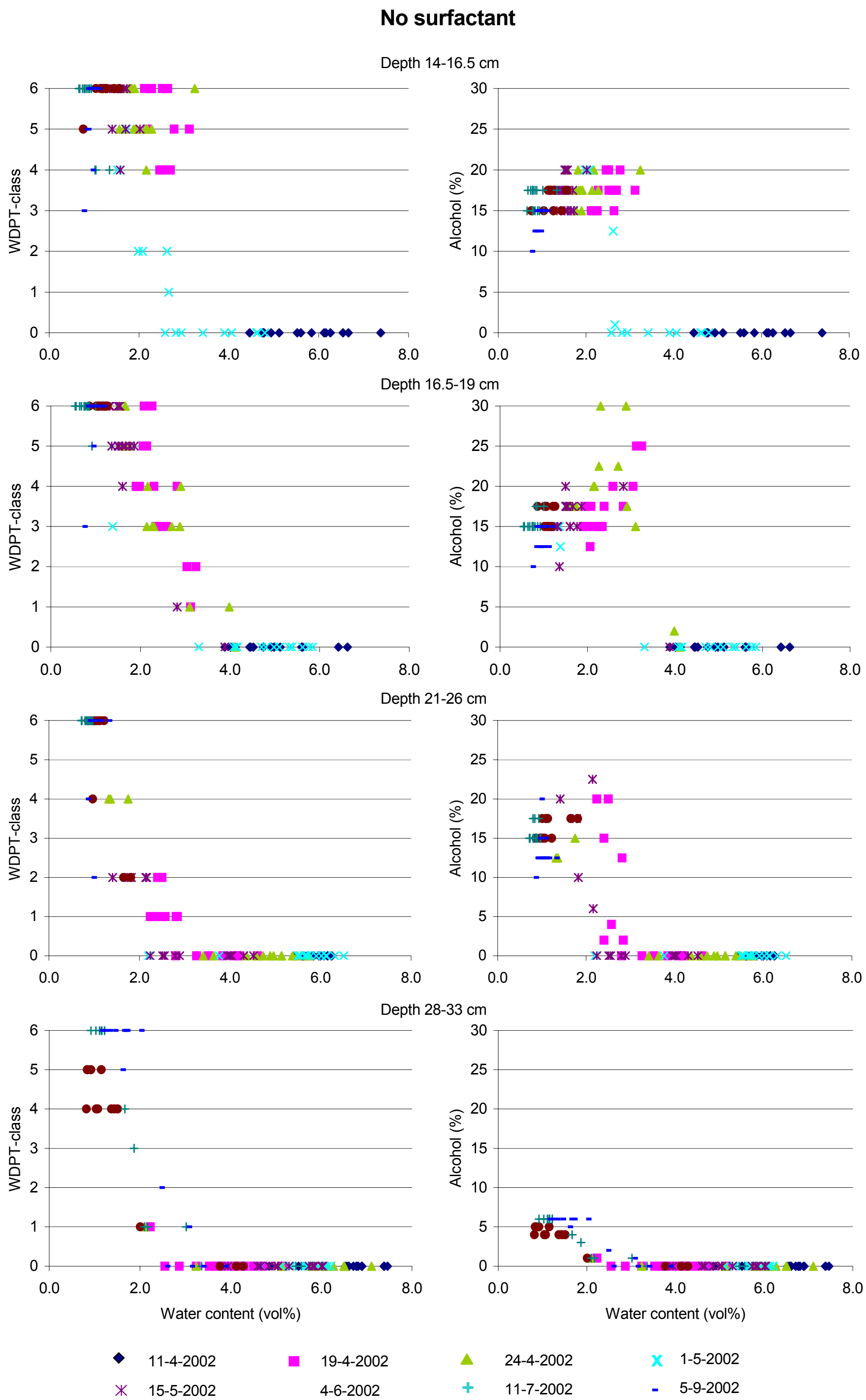

Figure 13 Relationships between soil water content and water repellency (WDPT class and Alcohol %) of the field-moist samples taken at four depths in the untreated plot on eight, separately indicated, sampling dates (n = 120).

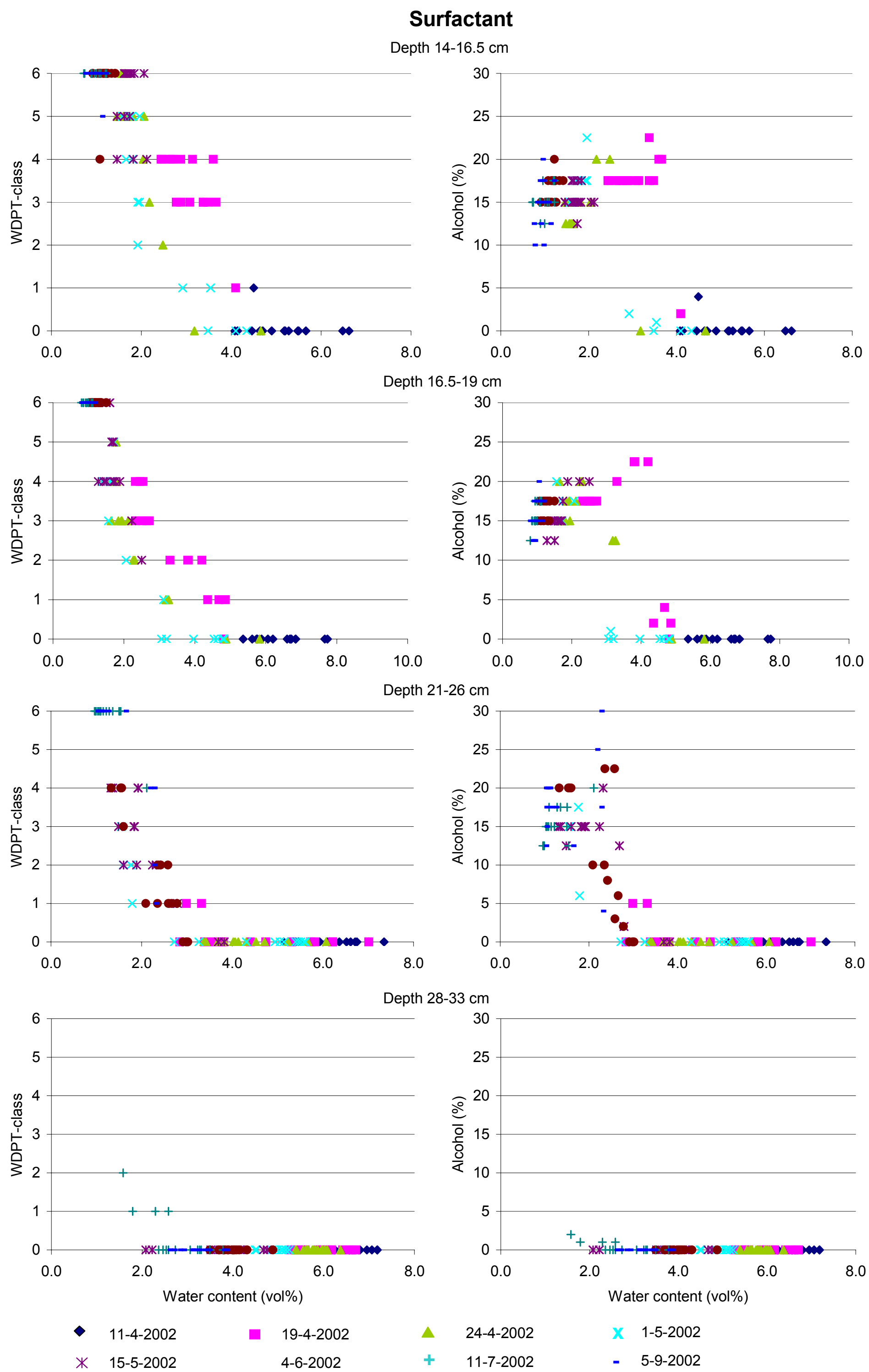

Figure 14 Relationships between soil water content and water repellency (WDPT class and Alcohol %) of the field-moist samples taken at four depths in the former Primer®604 treated plot on eight, separately indicated, sampling dates (n = 120).

Table 1 Relationship between the persistence and degree of actual water repellency of soil samples taken at 8 depths (n = 120) in the 8 transects of the untreated plot between 11 April and 5 September 2002. The median alcohol values occur in the blue zones.

		Alcohol (%)													
Depth (cm)	WDPT class	0	1	2	4	6	8	10	12.5	15	17.5	20	22.5	25	>27.5
0-2.5	2														**2**
	3									1	41	**47**	7	1	4
	4											**12**	4	1	
2.5-5	1												**1**		
	2										1		3		**5**
	3										16	**30**			5
	4										5	**39**	12		
	5											**3**			
7-9.5	0	**1**													
	1			1	3	**1**	1			1		2			
	2									1			1		**3**
	3								2	2	**6**				
	4									3	**19**	22			
	5									4	**12**	10			
	6									4	6	**13**	2		
9.5-12	0	**9**													
	1			2	**2**		1								
	2											**1**			
	3									**1**	1				
	4								3	**4**	3	3			
	5								2	**16**	13	2			
	6									14	**30**	13			
14-16.5	0	**24**													
	1		**1**												
	2								1			**2**			
	3							1							
	4								1	3	**4**	4			
	5								2	4	**8**	4			
	6								1	**30**	25	5			
16.5-19	0	**30**													
	1			1						**1**		1		1	
	2											**1**		1	
	3							1	1	1	1	**2**	2		2
	4									4	**3**	1			
	5							1	2	**5**	6				
	6								5	**30**	16	1			
21-26	0	**60**													
	1			2	**1**				1			1			
	2					1		1		1	**3**	3	1		
	4							1	**2**	2					
	6								11	**23**	6				
28-33	0	**83**													
	1			1		1	**3**	1	1						
	2											**1**			
	3											**1**			
	4								1	2	**2**	2			
	5								1	**5**					
	6								**9**	4	2				

Table 2 Relationship between the persistence and degree of actual water repellency of soil samples taken at 8 depths (n = 120) in the 8 transects of the former Primer®604 treated plot between 11 April and 5 September 2002. The median alcohol values occur in the blue zones.

WDPT class	Alcohol (%)														
	0	1	2	3	4	5	6	8	10	12.5	15	17.5	20	22.5	25	≥27.5
1								6	**38**	13	12		1			
2								1	16	**16**	13	3				
3													**1**			
1					1				1	6	**8**	2				
2									7	25	**34**	17	9			1
3											2	**3**	3	1		
0	**1**															
1					2		1	**1**		1	2		1			
2										2			**4**	2		
3								2	4	6	**19**	15	6	3		
4											5	**14**	13			
5											3	**8**	2			
6												**2**	1			
0	**11**															
1			2		**1**				1							
2												**1**				
3									1		1	**2**	1	1		
4									1	1	6	**16**	4	1		
5										7	7	**15**	2			
6										1	13	**23**	1			
0	**19**															
1		1	**2**		1											
2												**1**	1			
3												**6**	2	2		
4											5	**8**	1			
5										4	**11**	2				
6									2	6	**25**	19	2			
0	**25**															
1		1	2		**1**					2						
2												1	**4**	3		
3											1	**7**	3			
4										2	**7**	5	1			
5											**5**					
6										5	**25**	19	1			
0	**59**															
1			2	1	1	**2**	2		2	1						
2								1			4	**1**	1	2		1
3										1	**3**		1			
4											4	**1**	4		1	
6										6	**7**	7	5			
0	**116**															
1			**2**								1					
2													**1**			

3.1.5. Potential Soil Water Repellency

The persistence of potential water repellency of the transects, sampled in the untreated and former Primer®604 treated plots between 11 April and 5 September 2002, has been shown in the 16 contour plots of Figure 15. It is remarkable that the persistence of potential water repellency of the six transects sampled in April is less extreme, in comparison with the transects sampled between 15 May and 5 September. These differences may be the result of the higher soil water contents and the lower severity of the actual water repellency in the April transects, in comparison with the transects sampled later. Noteworthy is also the lower severity of the persistence of potential water repellency in the surface layer of the Primer®604 treated plot, and the greater difference in severity with the underlying soil, when compared with the surface layer of the untreated plot.

Only small differences in the severity of the degree of potential water repellency have been detected between the eight transects in the untreated plot, and a decrease in severity with depth was noticed in all the transects (Fig. 16). The upper part of the soil profile in the transects, sampled in the former Primer®604 treatred plot on 19 and 24 April, 1 and 15 May, and 11 July, shows a shift to a lower alcohol percentage class in comparison with the untreated plot.

That the severity of the persistence of potential water repellency at 0-2.5 cm and 2.5-5 cm depth in the former Primer®604 treated plot was significantly less when compared with the untreated plot, has also been illustrated by the diagrams of Figure 17 and Figure 18. It is remarkable again that samples taken at depths of 9.5-26 cm in the transects between 1 May and 5 September exhibit more extreme potential water repellency, when compared with the April transects (see Fig. 17 and Fig. 18). This is supposed to be the result of the lower soil water contents and the more severe persistence of the actual water repellency of the field-moist samples in the later transects (compare Figs. 17 and 18 also with Figs. 4, 5, 7, 8).

Figure 19 and Figure 20 show that the degree of potential water repellency, measured with the alcohol percentage test, differed only slightly between the transects sampled in the untreated plot between 11 April and 5 September. On the other hand, pronounced differences in degree of potential water repellency had been established in the former Primer®604 treated plot, for instance with relatively high alcohol percentages measured for samples from the 4 June transect, and relatively low percentages for samples from the 5 September transect.

3.1.6. Relationship Between Persistence and Degree of Potential Water Repellency

Table 3 shows the relationship between the persistence and the degree of potential water repellency for the different layers of the 8 transects in the untreated plot. The highest alcohol percentages (15-20%) were measured in the upper 5 cm of the profile, although the WDPT classes varied between 3-6. On the other hand, alcohol percentages of 10-15% were measured at depths of 16.5-19, 21-26, and 28-33 cm on extremely water repellent samples with WDPT values exceeding six hours (class 6), thus indicating that a relatively low degree can go hand in hand with a high persistence. The positive relationship between the persistence and degree of potential water repellency in the untreated plot is most pronounced at 16.5-19 and

21-26 cm depth. Table 3 shows evidently that the persistence or stability of potential water repellency considered in relation to its degree increases with depth. The tendency of this persistence/degree ratio to increase with depth is undoubtedly related with the characteristic and content of the organic matter, as also stated by Dekker and Ritsema (1994) and Dekker (1998).

Table 4 shows the relationship between the persistence and the degree of potential water repellency for the different layers of the 8 transects in the former Primer®604 treated plot. At 0-2.5, 2.5-5, and 7-9.5 cm samples were found to have lower alcohol percentages, when compared with the untreated plot. However, the highest alcohol percentages were also in the treated plot measured on samples from the topsoil. A positive relationship between persistence and degree of potential water repellency is most pronounced at depths of 14-16.5 cm, 16.5-19 cm, and 21-26 cm. The samples taken in the eight transects of the former Primer®604 treated plot show also clearly an increase with depth of the persistence/degree ratio of the potential soil water repellency (Table 4).

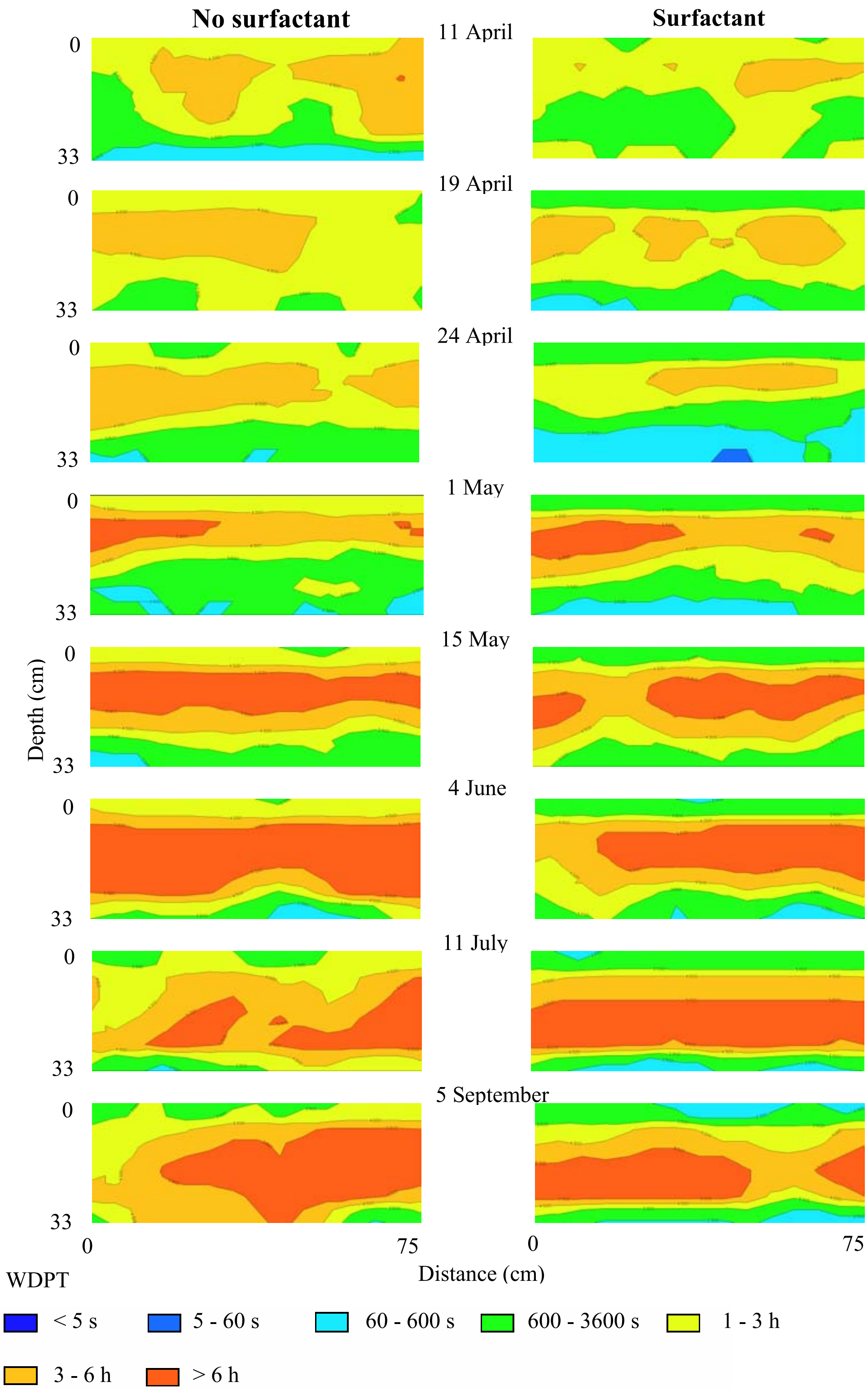

Figure 15 Contour plots (width 75 cm; depth 33 cm) of the persistence of potential soil water repellency at the two sites between 11 April and 5 September 2002.

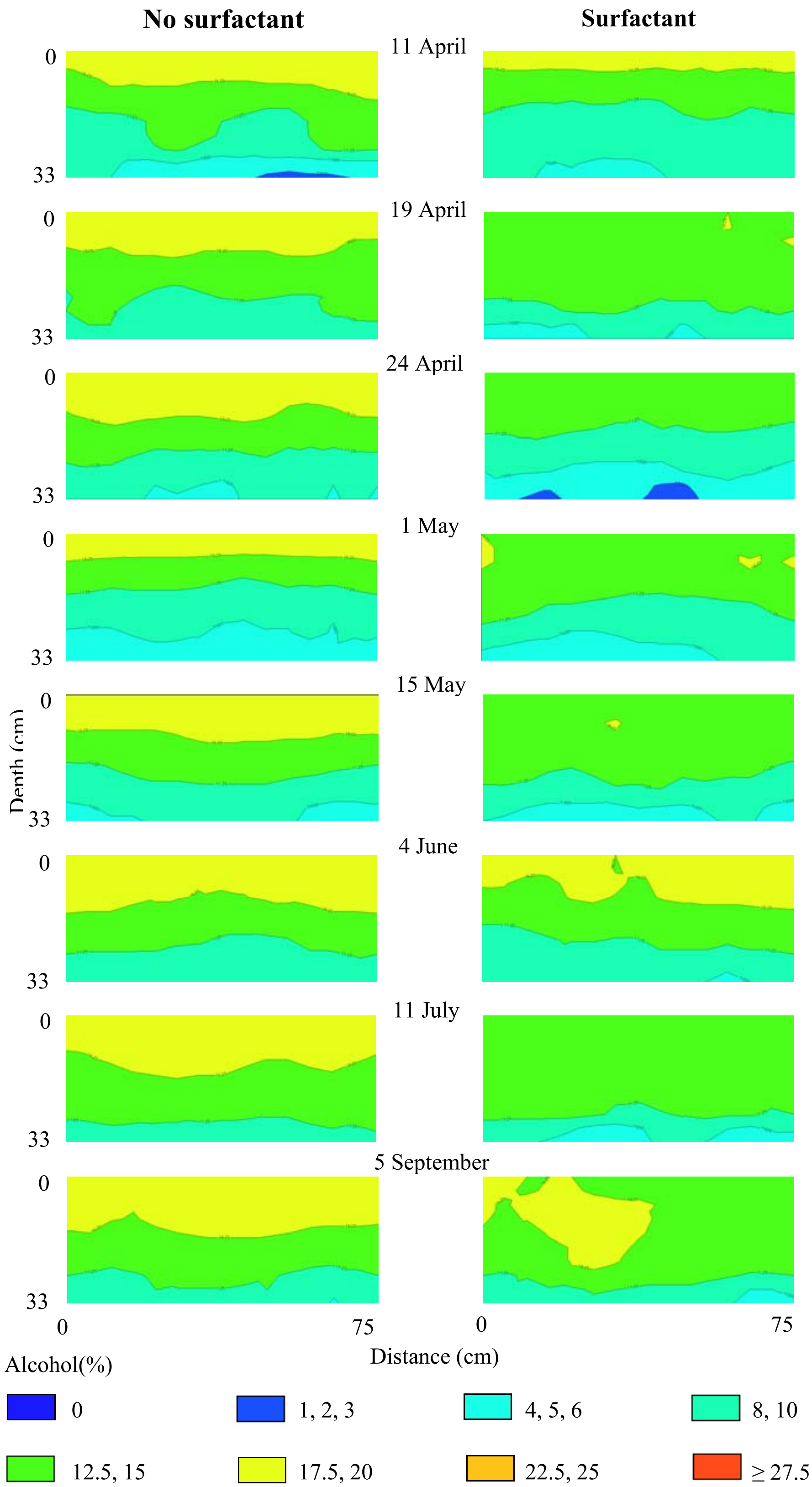

Figure 16 Contour plots (width 75 cm; depth 33 cm) of the degree of potential soil water repellency at the two sites between 11 April and 5 September 2002.

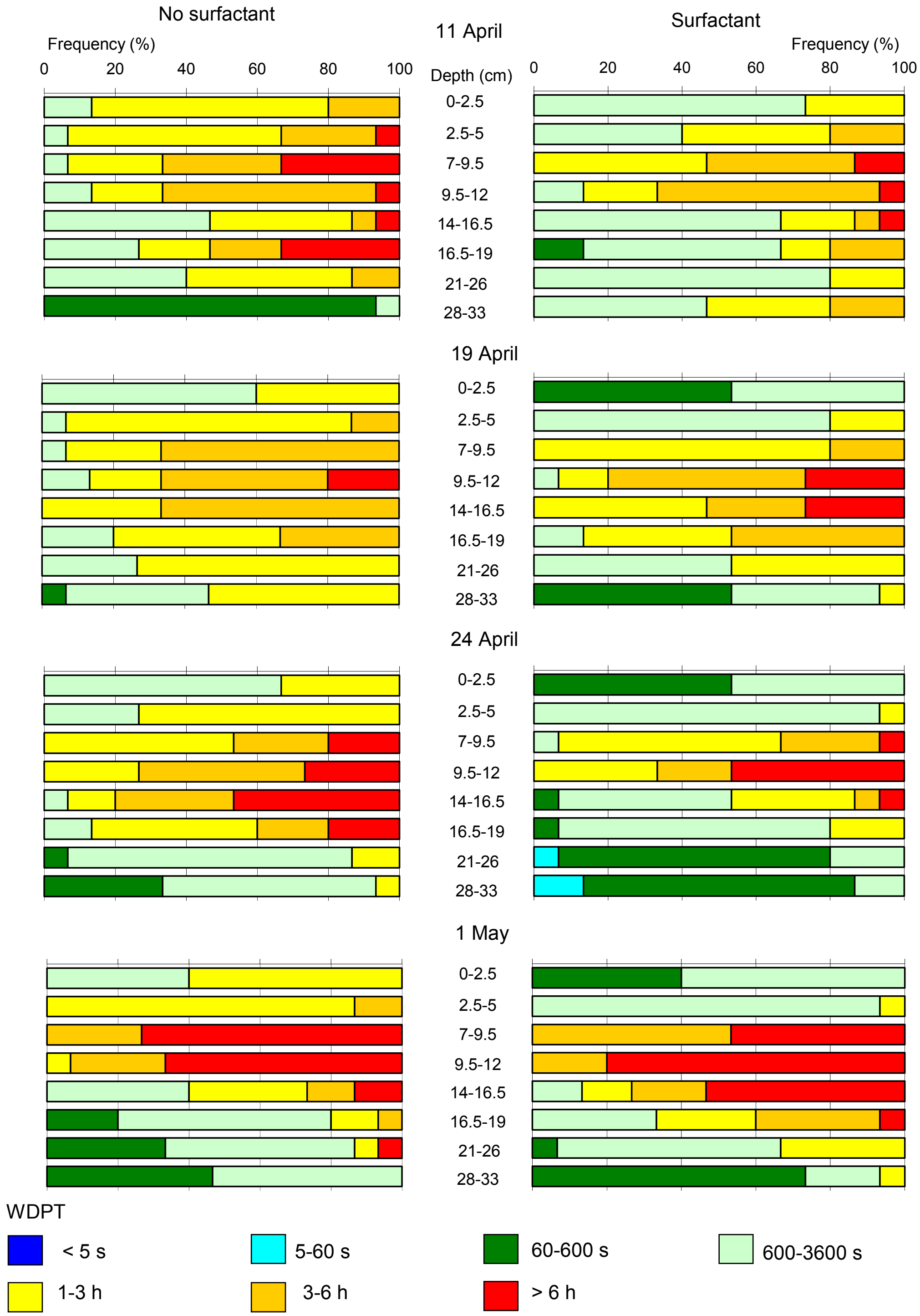

Figure 17 Relative frequency of the persistence of potential water repellency of soil samples, taken between 11 April and 1 May 2002 at 8 depths, in the untreated and in the former Primer®604 treated plot (n = 15).

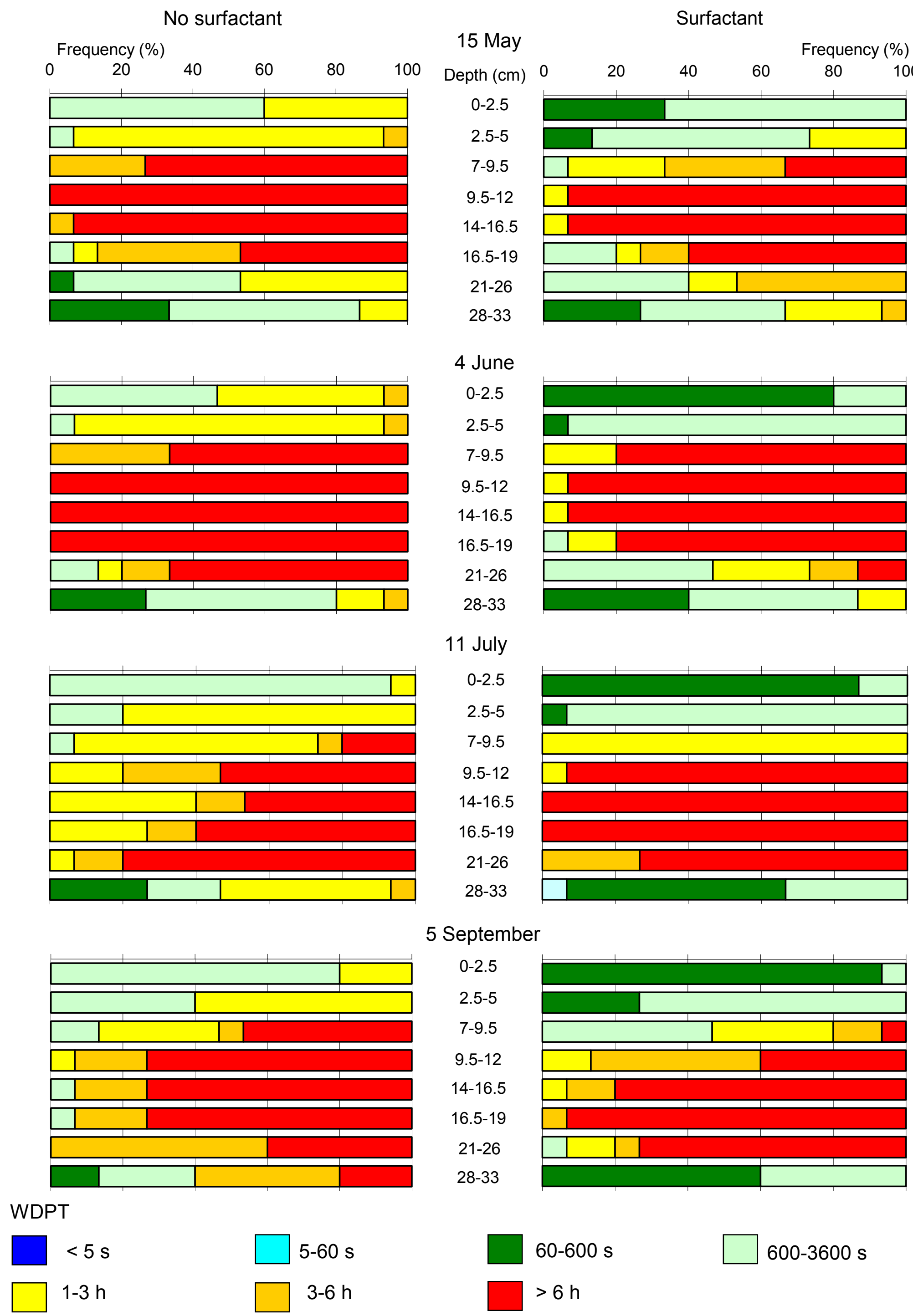

Figure 18 Relative frequency of the persistence of potential water repellency of soil samples, taken between 15 May and 5 September 2002 at 8 depths, in the untreated and in the former Primer®604 treated plot (n = 15).

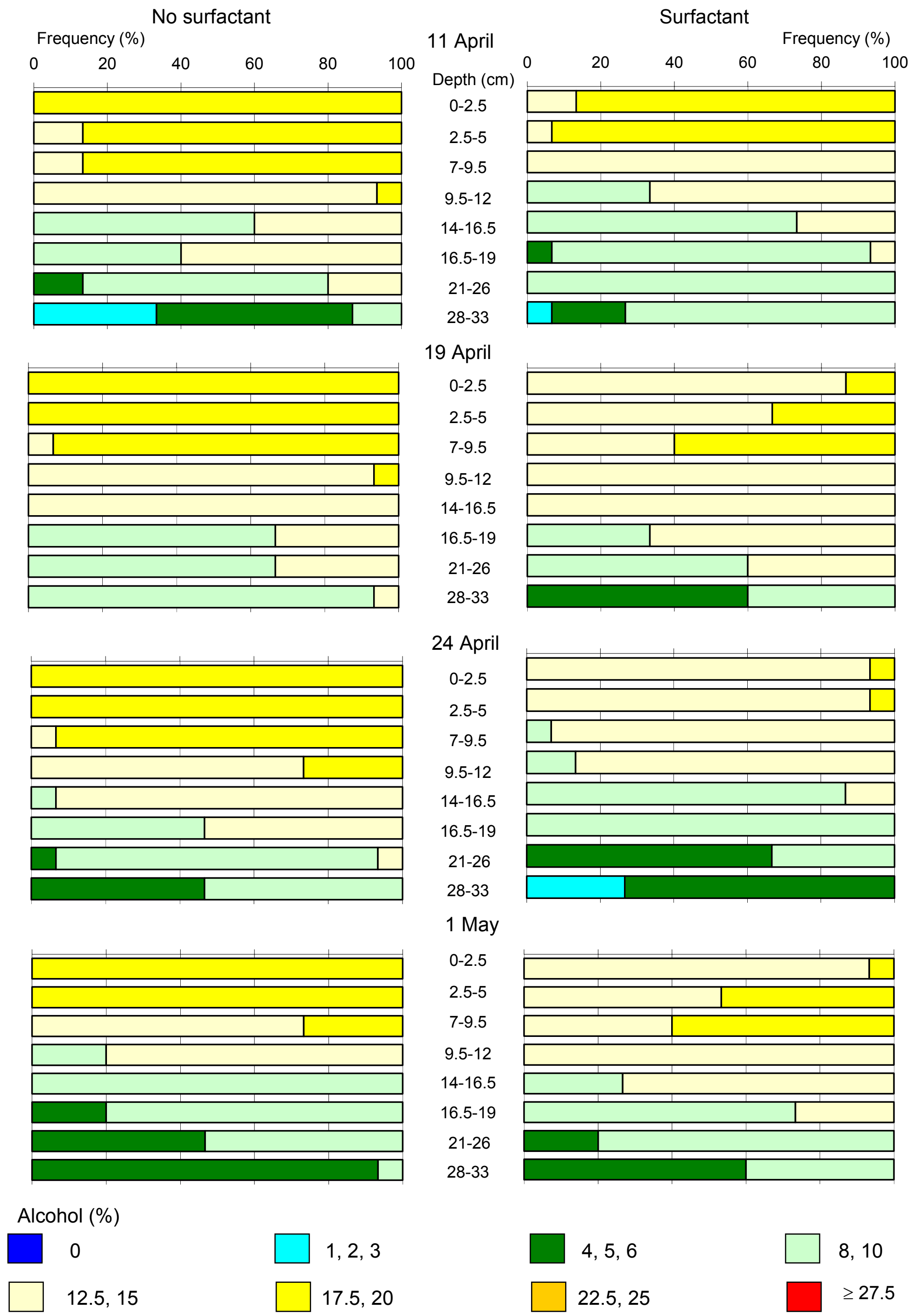

Figure 19 Relative frequency of the degree of potential water repellency of soil samples, taken between 11 April and 1 May 2002 at 8 depths, in the untreated and in the former Primer®604 treated plot (n = 15).

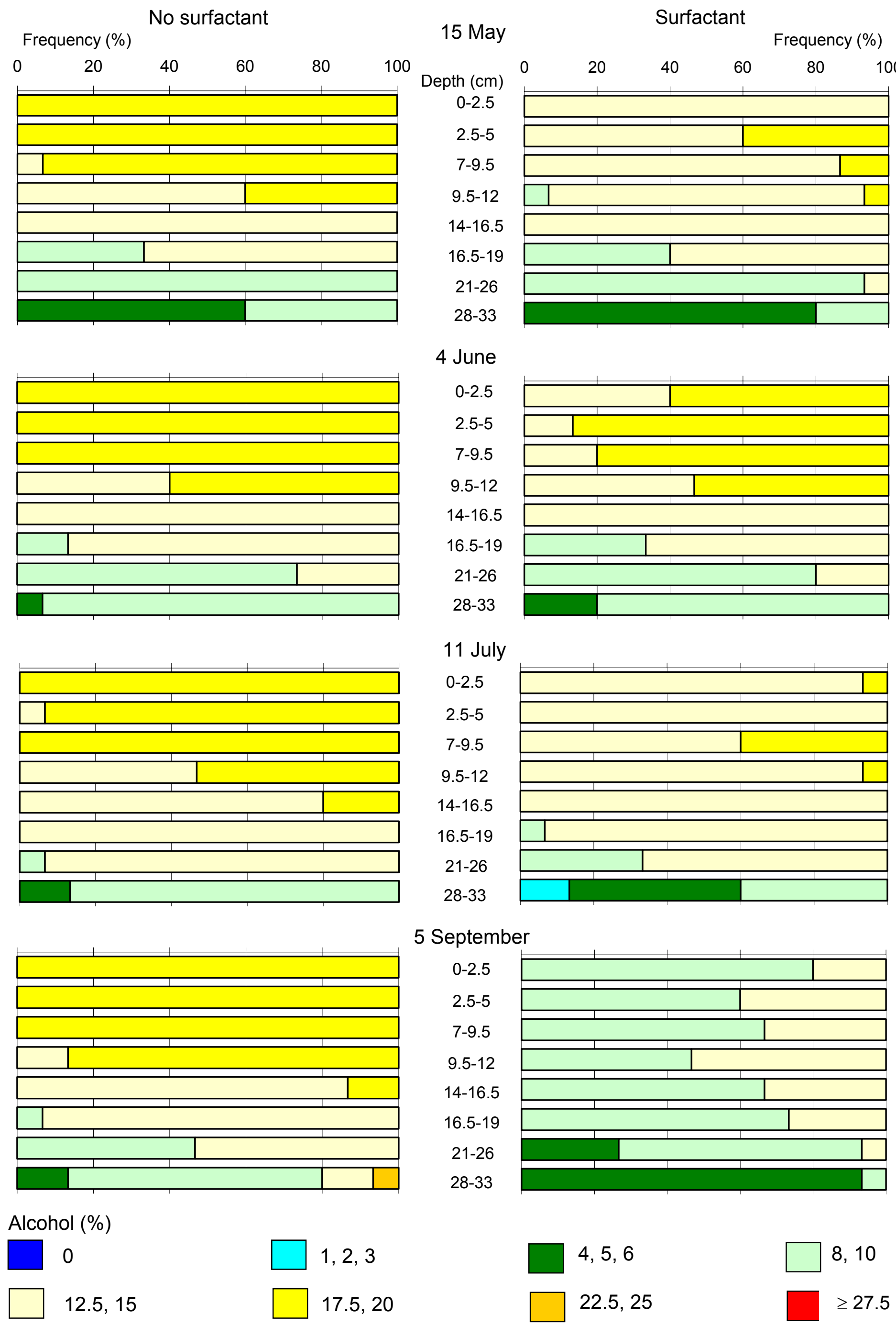

Figure 20 Relative frequency of the degree of potential water repellency of soil samples, taken between 15 May and 5 September 2002 at 8 depths, in the untreated and in the former Primer®604 treated plot (n = 15).

Table 3 Relationship between the persistence and degree of potential water repellency of soil samples taken at 8 depths (n = 120) in the 8 transects of the untreated plot between 11 April and 5 September 2002. The median alcohol values occur in the blue zones.

	WDPT	Alcohol (%)										
Depth (cm)	class	2	3	4	5	6	8	10	12,5	15	17,5	20
0-2.5	3										9	60
	4										1	46
	5											4
2.5-5	3										2	15
	4									2	4	86
	5										1	9
	6									1		
7-9.5	3										2	3
	4									2	17	12
	5								2	4	24	4
	6								2	6	33	9
9.5-12	3								3	1		
	4								2	10	3	
	5							2	3	24	5	
	6							1	8	24	34	
14-16.5	3						2	12		1		
	4							7	3	13	1	
	5							2	6	14	2	
	6							2	10	43	2	
16.5-19	2					3						
	3						7	12		1		
	4							15	7	2		
	5							4	17	2		
	6							5	18	27		
21-26	2				3	1	2	1				
	3				3	3	19	11	3			
	4							25	4	1		
	5							6	9			
	6							11	13	5		
28-33	2	3	2	5	8	15	8	1				
	3			2	5	8	17	15				
	4						5	14	1			
	5							6	2			
	6							2	1			

Table 4 Relationship between the persistence and degree of potential water repellency of soil samples taken at 8 depths (n = 120) in the 8 transects of the former Primer®604 treated plot between 11 April and 5 September 2002. The median alcohol values occur in the blue zones.

Depth (cm)	WDPT class	Alcohol (%)											
		1	2	3	4	5	6	8	10	12,5	15	17,5	20
0-2.5	2									22	33	11	
	3									1	34	15	
	4											1	3
2.5-5	2									2	5	1	
	3									4	57	33	
	4											11	4
	5												3
7-9.5	3									2	3	3	1
	4									4	38	13	
	5								1	4	14	9	3
	6										11	14	
9.5-12	3								2		1		
	4								5	1	9		
	5								1	9	18	1	1
	6									5	51	15	1
14-16.5	2							1					
	3							1	18				
	4								7	8	5		
	5								1	5	4	1	
	6									20	45	4	
16.5-19	2						1	2					
	3							6	24				
	4								14	4			
	5								7	11			
	6								3	30	14	4	
21-26	1				1								
	2					3	7	2					
	3						2	12	31	1			
	4								14	9			
	5								11	3			
	6								6	14	3	1	
28-33	1	2	1										
	2		2	1	7	19	19	6	4				
	3			1	1	3	6	17	13	1			
	4						3	7	3				
	5						1	2	1				

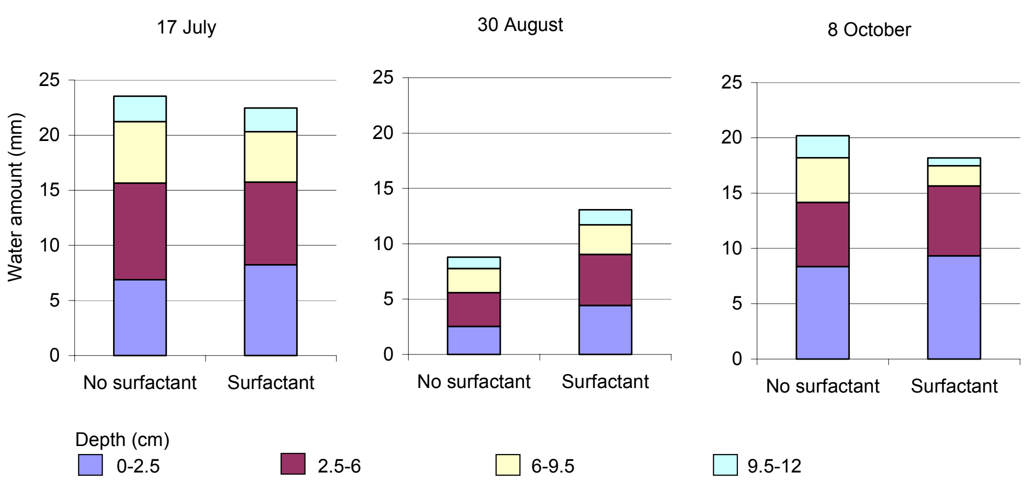

Figure 21 Mean amounts of mm water in the upper four soil layers (n = 15) of the untreated and ACA 1897 treated plot on 17 July, 30 August, and 8 October 2002.

3.2. Short-term Effect of ACA 1897

3.2.1. Amounts of Water in the Upper 12 cm of the Soil Profiles

The mean amounts of water in the topsoil, between 0 and 12 cm depth, differed only slightly between the untreated plot and the treated plot after 6 ACA 1897 applications, as demonstrated with the diagrams of 17 July in Figure 21. The relatively high amounts of water in the soil profiles were partly a consequence of the weekly 10 mm irrigations since 5 June. The lower amounts of irrigation water resulted in relatively drier soil profiles in the transects of 30 August. The mean amount of water in the surface layer between 0-6 cm depth was at this moment significantly higher in the plot after 12 ACA applications, when compared with the untreated plot. However, on 8 October 2002, after 18 ACA applications, only slightly higher mean amounts of water were detected in the surface layer of the treated plot, and somewhat lower amounts at 6-12 cm depth, in comparison with the untreated plot (Fig. 21).

3.2.2. Actual and Potential Soil Water Repellency of the Transects

All field-moist samples taken at 0-2.5, 2.5-5, 7-9.5, and 9.5-12 cm depth in the untreated plot and in the treated plot after 6 applications of ACA 1897, were wettable, as is shown in Figure 22 and Figure 23. A significant difference in persistence of actual soil water repellency was detected on 30 August, after 12 ACA applications. At all four depths 14 to 47% of the samples were wettable in the treated plot, whereas all samples in the untreated plot were slightly to extremely water repellent. On 8 October, after 18 treatments with ACA, more wettable samples have been detected at 0-2.5 cm and 2.5-5 cm in the treated plot, when compared with the untreated plot. It is remarkable that on the other hand at 7-9.5 cm and 9.5-12 cm a larger part of the samples from the treated plot exhibited water repellencey, and the persistence of these samples was also more extreme (compare Figs. 22 and 23).

The potential soil water water repellency after drying the samples at 65^0C has been illustrated in the right hand diagrams of Figure 22 and Figure 23. The persistence of potential soil water repellency was significantly lower at 0-2.5 cm depths in the treated plot on 30 August and 8 October, after respectively 12 and 18 applications, when compared with the untreated plot.

The degree of actual and potential water repellency of the soil samples taken in the untreated and ACA treated plot on the three sampling dates has been depicted in Figure 24 and Figure 25. Noteworthy are the extreme high alcohol percentages, often exceeding 27.5%, detected for the field-moist samples in both plots on 30 August an 8 October 2002. It is also remarkable that the degree of potential water repellency, after drying the samples at 65^0C, is often the same for wettable and water repellent field-moist samples, indicating an increase in severity for wettable samples and a decrease in severity for water repellent samples. However, here we state that the use of the alcohol percentage test on the field-moist samples may overestimate the degree of soil water repellency. A significantly lower degree of potential water repellency was determined at 0-2.5 and 2.5-5 cm depth in the treated plot from 8 October, in comparison with the untreated plot.

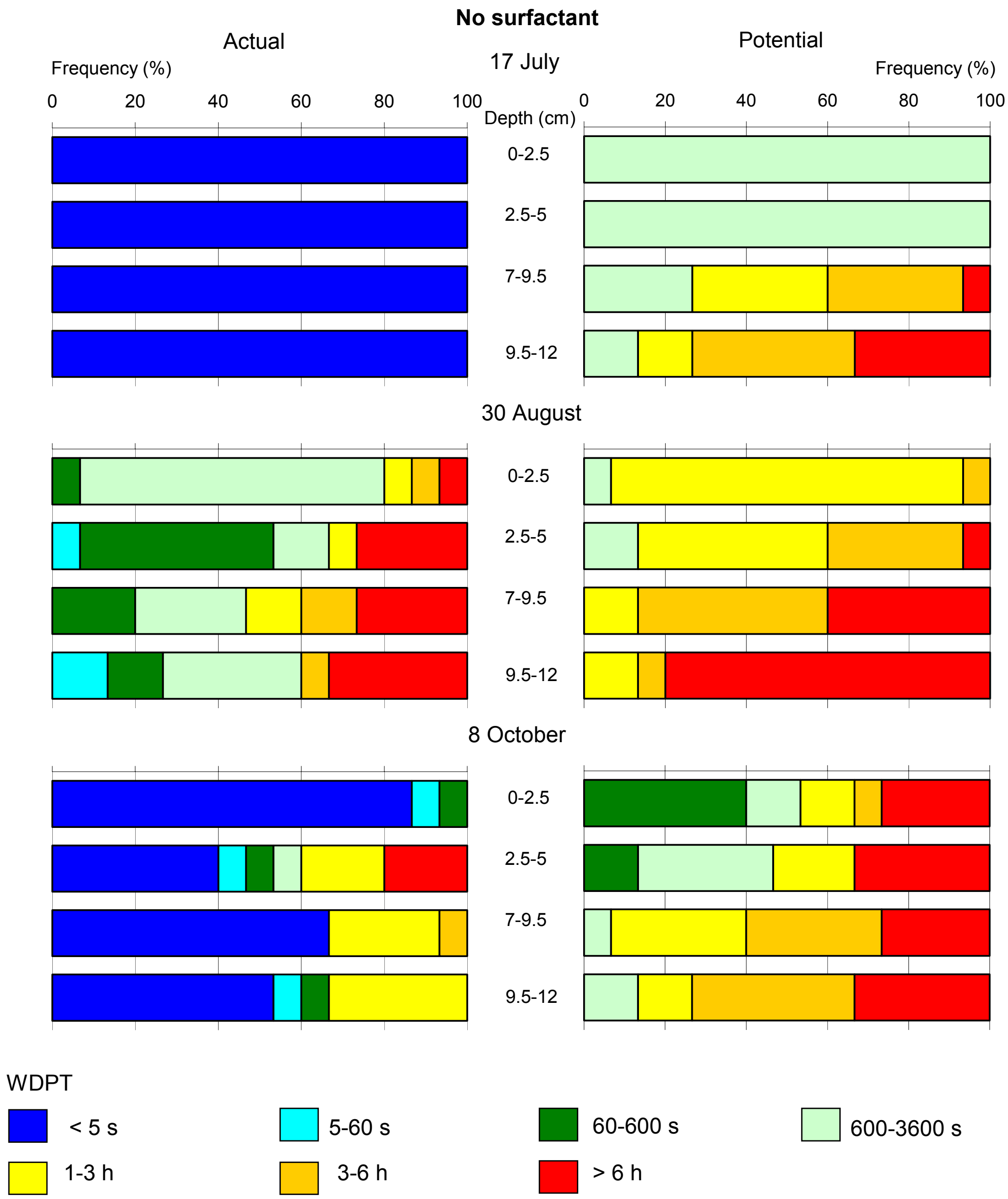

Figure 22 Relative frequency of the persistence of actual and potential water repellency of soil samples, taken at four depths in the untreated plot on 17 July, 30 August, and 8 October 2002 (n = 15).

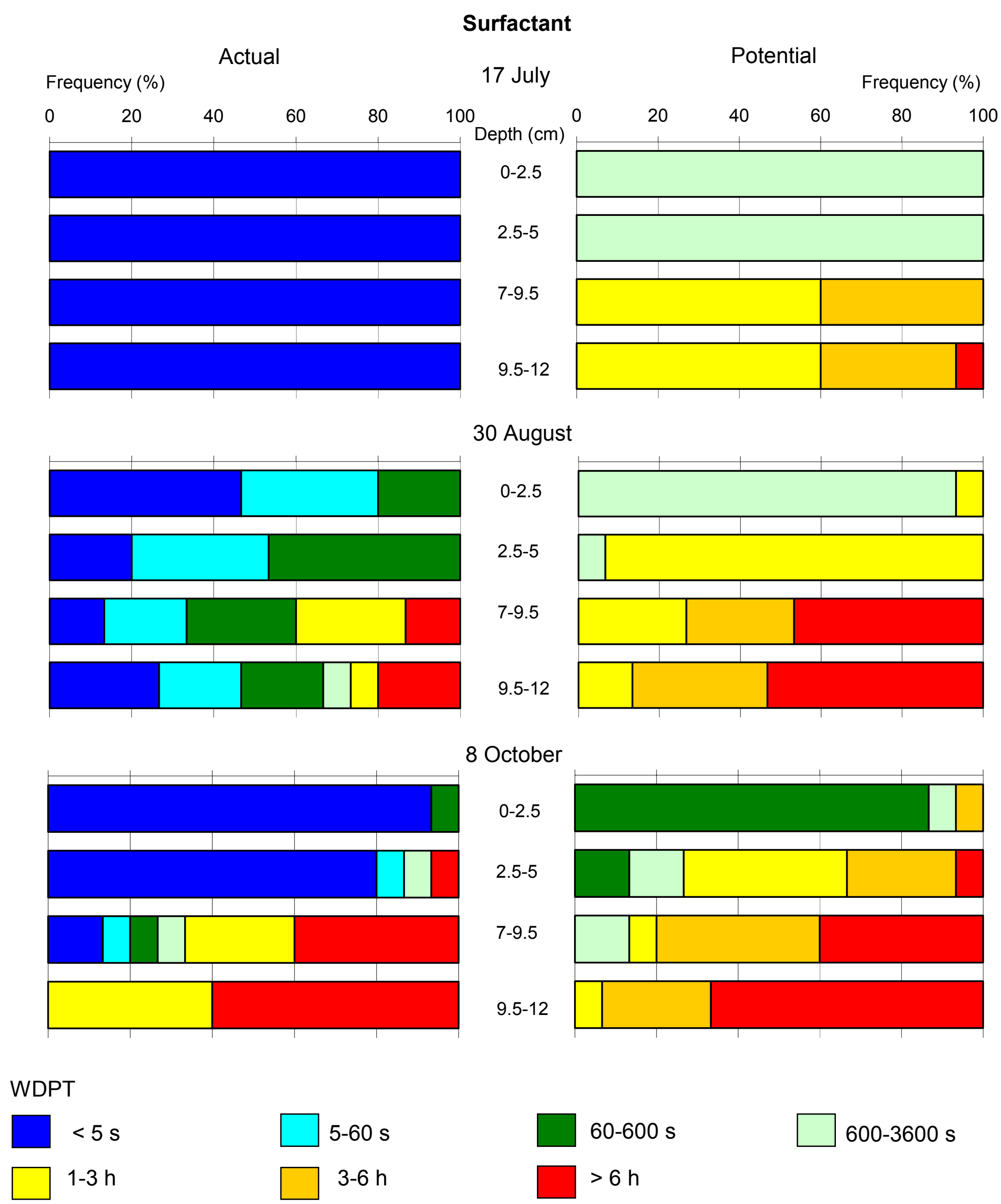

Figure 23 Relative frequency of the persistence of actual and potential water repellency of soil samples, taken at four depths in the ACA treated plot on 17 July, 30 August, and 8 October 2002 (n = 15).

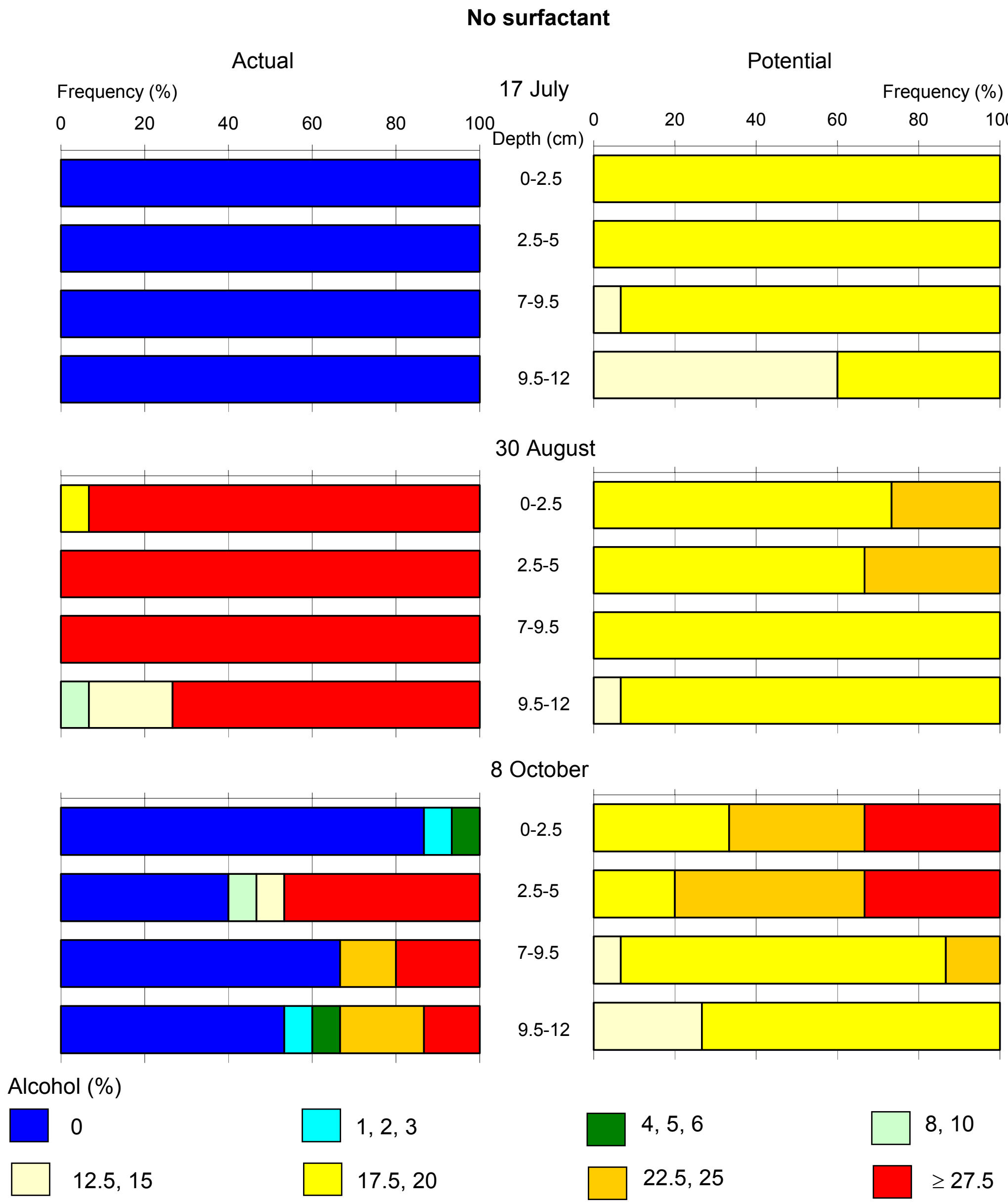

Figure 24 Relative frequency of the degree of actual and potential water repellency of soil samples, taken at four depths in the untreated plot on 17 July, 30 August, and 8 October 2002 (n = 15).

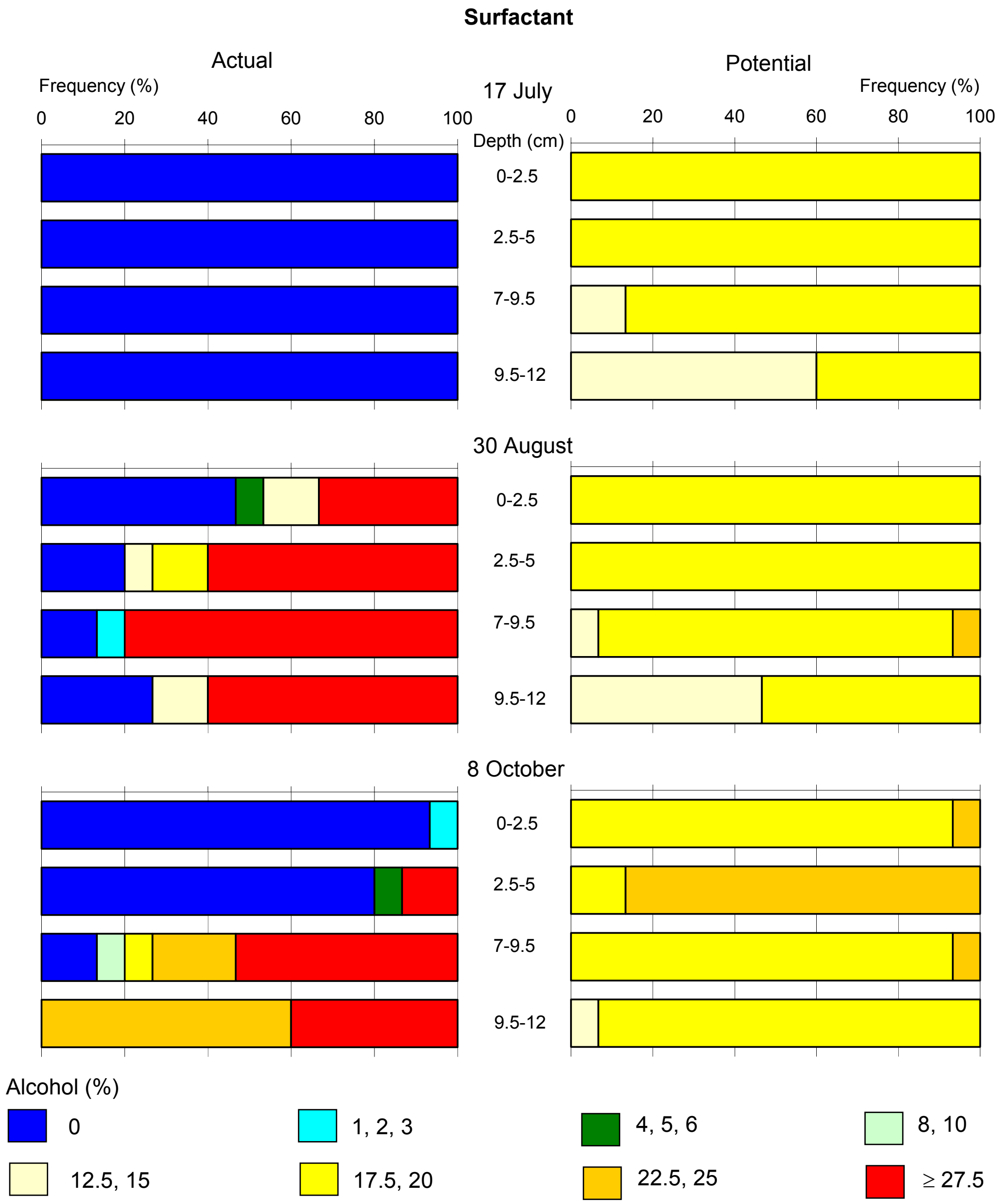

Figure 25 Relative frequency of the degree of actual and potential water repellency of soil samples, taken at four depths in the ACA treated plot on 17 July, 30 August, and 8 October 2002 (n = 15).

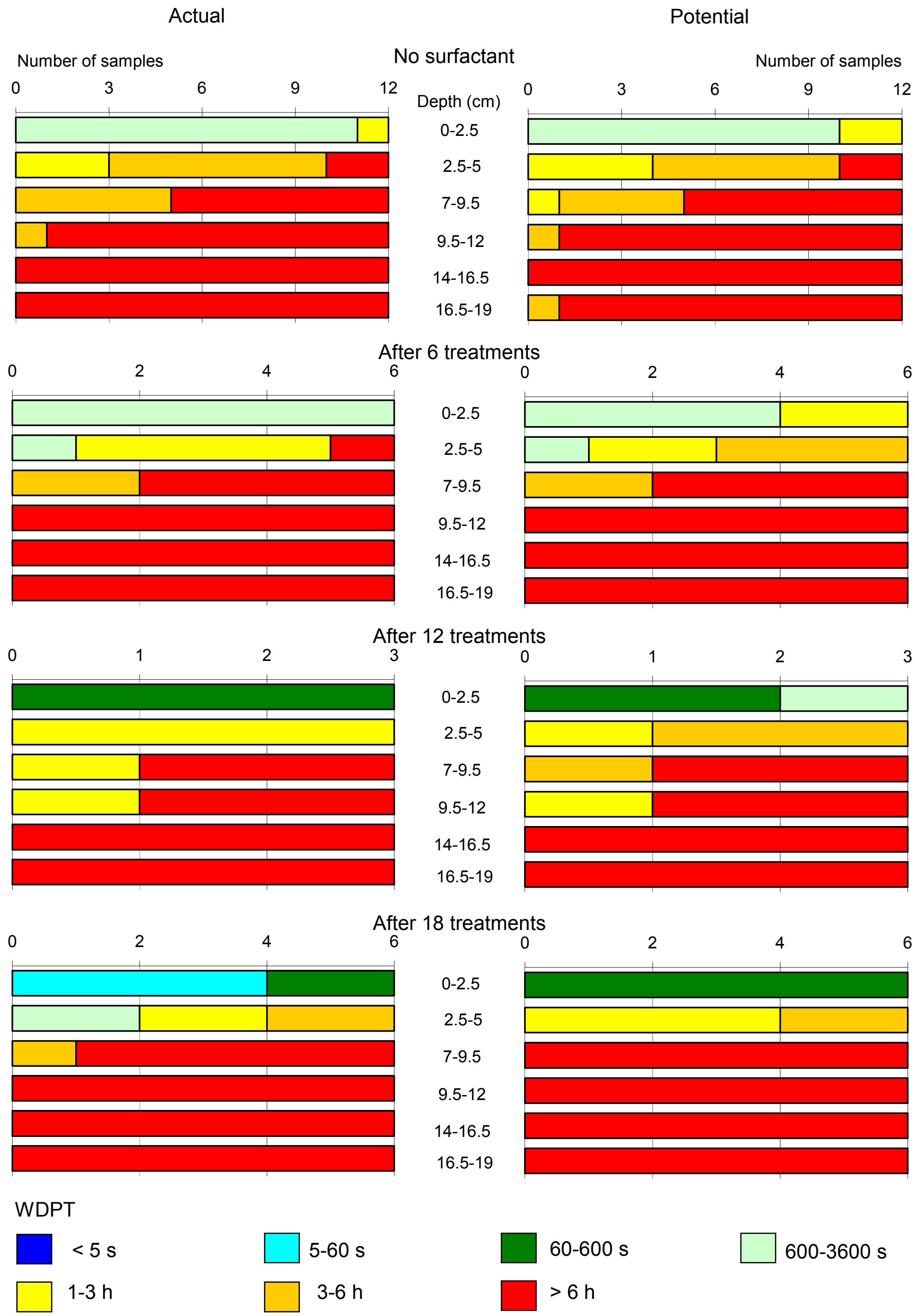

Figure 26 Frequency of the persistence of actual and potential water repellency of soil samples at six depths from the dehydrated soil columns, taken in the untreated and 6, 12, and 18 times, ACA treated plot (n = 2, 6, or 12).

3.2.3. Actual and Potential Soil Water Repellency of the Dehydration Experiment

All twelve samples taken at 2.5-5, 7-9.5, 9.5-12, 14-16.5, and 16.5-19 cm depth in the dehydrated four soil columns, carved out in the untreated plot exhibited extreme water repellency, whereas at 0-2.5 cm depth nearly all samples showed severe water repellency (Fig. 26). Further drying of these samples at 65^0C scarcely influenced the severity of the persistence of soil water repellency.

Six applications of ACA 1897 influenced only slightly the persistence of the actual and potential soil water repellency at 0-2.5, and 2.5-5 cm depth. A significant decrease in persistence of actual and potential water repellency occurred at 0-2.5 cm depth after 12 applications, followed by a further decrease after 18 applications (Fig. 26).

ACA 1897 treatments are showing a tendency of a lower degree of actual water repellency in the surface layer at 0-2.5 cm depth with increasing applications, as is illustrated in the left-hand diagrams of Figure 27. At this depth alcohol percentages of 17.5-20% were detected on samples from the dehydrated columns of the untreated plot and of 4-10% on samples from the columns taken after 18 applications of the surfactant ACA 1897. However, drying of these samples at 65^0C resulted in an increase of the alcohol percentages. On the other hand, the slight differences are remarkable between the degree of actual and potential water repellency of the other samples from the dehydrated columns (Fig. 27).

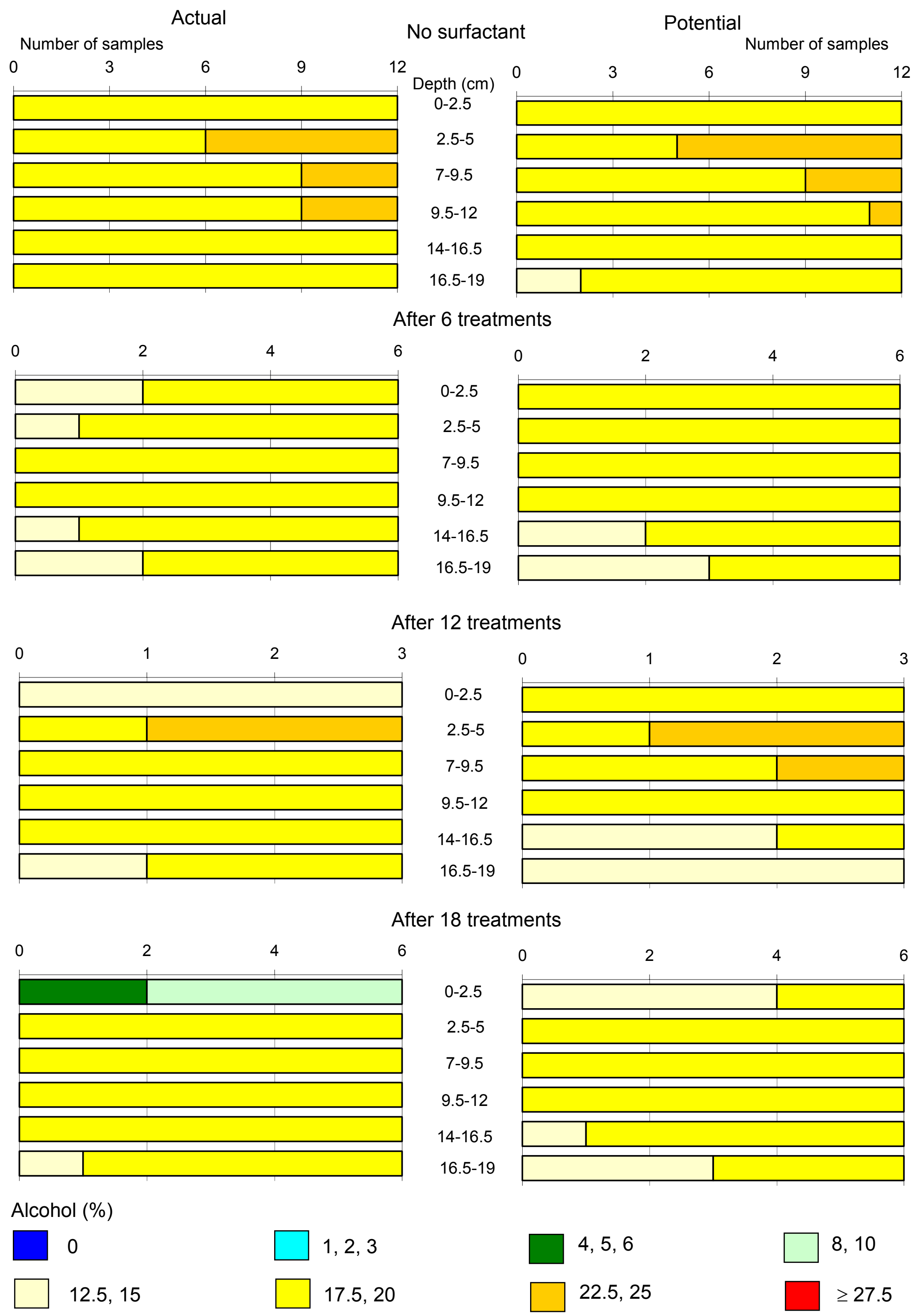

Figure 27 Frequency of the degree of actual and potential water repellency of soil samples at six depths from the dehydrated soil columns, taken in the untreated and 6, 12, and 18 times, ACA treated plot (n = 2, 6, or 12).

4. Conclusions

4.1. Long-term Effect of Primer®604

Slightly water repellent and wettable dune sand with grass cover were found to be altered into extremely water repellent soil within one week of dehydration under shelters. The most extreme water repellency, with water drop penetration times of more than six hours, were detected in large parts of transects sampled in the untreated and former Primer®604 treated plot between 11 July and 5 September 2002.

It is striking that the surface layer of the former Primer®604 treated soil was always less water repellent in comparison with the untreated soil. Thus, the effect of surfactant applications is still notable nearly nine months after the last application.

In general, slightly lower alcohol percentages have been detected in the transects of the Primer®604 treated soil, when compared with the untreated soil. Thus, indicating a lower degree of actual water repellency.

4.2. Short-term Effect of ACA 1897

Significantly lower values for the persistence of actual and potential water repellency have been detected with the water drop penetration time test at 0-2.5 cm and 2.5-5 cm depth after 12 and 18 applications in the ACA treated plot, when compared with the untreated plot.

Extremely high alcohol percentages were detected for the field-moist samples in the untreated as well as the ACA treated plot. However, we state that the use of the alcohol percentage test on field-moist samples often overestimates the degree of soil water repellency.

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