Fungicide leaching from golf greens: Effects of root zone composition and surfactant use

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List of abbreviations: AZO, azoxystrobin; IPR, iprodion; LDS, localized dry spots; PRO, propiconazole; WDPT, water drop penetration time

ABSTRACT

Soil water repellency in golf putting greens may induce preferential 'finger flow' leading to enhanced leaching of surface applied fungicides. We examined the effects of root zone composition, treatment with a non-ionic surfactant and use of either the fungicide iprodion (3-(3,5-dichlorophenyl)-N-(1-methylethyl)2,4-dioxo-1-imidazoline-carboximide) or a combination of azoxystrobin (Methyl (E)-2-{2-[6-(2-cyanophenoxy) pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate) and propiconazole (1-[[2(2,4-Dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]1-H-1,2,4-triazole) on soil water repellency, soil water content distributions, fungicide leaching and turf quality during one year. Soil water repellency was measured both using the water drop penetration time test and tension infiltrometers. Our study was made on a three year old experimental green seeded with creeping bentgrass (*Agrostis stolonifera* L.) 'Penn A-4' at Landvik in SE Norway. The facility consists of 16 lysimeters with two different root zone materials, i) straight sand (1% gravel, 96% sand, 3% silt and clay, 0.4% (w/w) organic matter) (*SS*), and ii) straight sand mixed with garden compost to an organic matter content of 2.1% (Green Mix (*GM*)). Results showed that surfactant treatment reduced soil water repellency and the spatial variation in soil water contents. Fungicide leaching was close to zero for the *GM* lysimeters probably due to stronger sorption. Concentrations in the drainage water from *SS* lysimeters often exceeded surface water guideline values for all three fungicides, but surfactant treatment dramatically reduced fungicide leaching from these lysimeters. In autumn and winter, surfactant treated plots were more infected with fungal diseases probably because of higher water content in the turfgrass thatch layer.

INTRODUCTION

Fungicides are applied to golf greens worldwide to improve turf quality. For example, in the coastal areas of Scandinavia fungicides are mainly used to control pink snow mould (*Microdochium nivale*) which is favored by the cold and relatively wet climate, particularly during the autumn. In Scandinavia as well as in other parts of the world, most golf greens are today constructed according to the US Golf Association (USGA) guidelines, which specify a 30 cm thick root zone of sandy material underlain by a coarse gravel drainage layer (US Golf Association, 2004). In the latest revision of these guidelines, there are no recommendations concerning the amount of organic carbon in the root zone. Greens built without organic matter or with very low organic matter content in the root zone have become increasingly popular because low organic carbon content leads to lower water contents in the root zone and thereby creates less favorable conditions for fungal diseases. The combination of high rainfall, a shallow root zone and low organic matter content constitutes a high-risk environment for fungicide leaching. This risk may be further aggravated by finger flow resulting from soil water repellency (Bauters et al, 1998), which is a common phenomenon in golf greens. Indeed, fungicides have often been detected in drainage water from golf greens and surface water influenced by runoff from golf courses (Petrovic et al., 1998; Cohen et al., 1999; Wu et al., 2002; Ludvigsen et al., 2004; Strömqvist and Jarvis, 2005).

The origin of soil water repellency is not well understood but it is generally assumed that it is caused by hydrophobic organic compounds produced by plant roots or soil microbes which coat the soil particles (Doerr et al., 2000). It has been shown that increased microbial activity (Hallett and Young, 1999) and fungal growth (White et al., 2000) may increase water repellency. However, the degree of water repellency is not proportional to the amount of organic matter. It is rather the composition of the soil organic matter that is important for the development of soil water repellency (Dekker and Ritsema, 1994; Doerr et al., 2000 and 2005; Morley et al., 2005). Soil water repellency has in the past been associated with coarse-textured soils because the available hydrophobic compounds have in these soils a smaller surface area to coat. However, in recent years it has become increasingly apparent that water repellency affects a variety of soil types (Dekker and Ritsema, 1996; Doerr et al., 2006; Jarvis et al., 2007). The importance of soil moisture for the occurrence and development of water repellency has been studied extensively (see e.g. review by Doerr et al., 2000). Generally, soil water repellency is insignificant or absent during wet conditions and most strongly developed during extended dry periods. Dekker et al. (2001) have shown that a critical soil water content exists below which soils become water repellent. This critical soil water content is dependent on the soil properties and on the wetting and drying history of the soil. Soil water repellency also affects solute transport in soils (van Dam et al., 1990; Hendrickx et al., 1993; Clothier et al., 2000). In water repellent soils, water and solutes may move rapidly in fingers bypassing large parts of the unsaturated zone. This increases the risk of pollution of receiving water bodies.

Localized dry spots (LDS) are one consequence of soil water repellency in golf greens. Turf grass areas showing symptoms of LDS are commonly treated with surfactants (Kostka, 2000). Many different surfactants exist, with different modes of action, but with the common feature that the surfactant molecules attach to hydrophobic soil surfaces rendering them wettable. Dekker et al. (2005) showed that the top 5 cm of surfactant treated grass-covered dune sand was less water repellent than untreated sand. The surfactant treatment also resulted in higher average water contents and lower critical water contents below which the soil was repellent. Surfactant treatment on golf greens has been shown to reduce water repellency and improve turf grass quality (Cisar et al., 2000; Kostka, 2000). However, much less is known about the effects of surfactants on solute transport. Nektarios et al. (2002) studied the infiltration and transport of bromide and a weakly sorbed dye tracer in water repellent dry sand in a two-dimensional slab chamber. Surfactant treatment resulted in a more uniform infiltration and greater retardation of the breakthrough of the tracers compared to the untreated control. To our knowledge the effects of surfactants on pesticide leaching have not been studied under realistic field conditions. The objective of this study was therefore to evaluate the effects of root zone composition and surfactant treatment on soil water repellency and leaching of fungicides from lysimeter golf greens.

MATERIALS AND METHODS

Site

The experiments were conducted in the lysimeter facility at Bioforsk Øst Landvik, Norway (58°19'N; 8°30'E, 5 m a s.l.) during 2006 and the spring of 2007. Air temperature (2 m above ground), soil temperature (10 cm depth) and precipitation during the experimental period were measured at Landvik meteorological station, about 200 m from the lysimeter facility. The facility consisted of 16 stainless steel lysimeters, each 2 m^2 in area, located in an experimental green in two separate blocks, constructed according to USGA guidelines. Each lysimeter consisted of a 30 cm root zone underlain by a 10–15 cm gravel layer. The gravel layer was placed directly on the sloping lysimeter bottom which directed any discharge to the outlet. The root zone layer was constructed with either straight sand, *SS*, or Green Mix®, *GM*, (Norsk Jordforbedring AS, Grimstad, Norway), the latter being *SS* amended with 20% (v/v) mature garden compost. Textural analyses indicated that the *SS* (1.2% fine gravel >2.0 mm, 12.2% very coarse sand 1.0–2.0 mm, 37.8% coarse sand 0.5–1.0 mm, 36.4% medium sand 0.25–0.5 mm, 6.9% fine sand 0.15–0.25 mm , 2.5% very fine sand 0.05-0.15 mm, 2.2% silt 0.002–0.05 mm and 0.8% clay <0.002 mm (European Turfgrass Laboratory, Stirling, Scotland, Jan 2004)) was slightly coarser than recommended by USGA. The green was seeded with creeping bentgrass (*Agrostis stolonifera*) 'Penn A-4' in September 2003. By 2006, the turf had developed a thatch layer which was 14 mm thick on the *SS* lysimeters and 19 mm on the *GM* lysimeters. Results from chemical soil analyses are presented in Table 1.

During the course of this study, the grass was mowed with walk-behind green mowers to a height of 3–5 mm (depending on the time of the season) three times per week and vertically cut and top dressed with 0.7 mm straight sand every two to three weeks. Starting in June, when the turf had recovered completely from winter injuries, wear was imposed by an artificial wear machine three times per week. At biweekly intervals, *SS* lysimeters received mineral fertilizer (Arena, Hydro Agri, Landskrona, Sweden) totaling

230 kg N, 30 kg P and 190 kg K ha^{-1} over the season while *GM* lysimeters received Arena and ammonium sulfate totaling 130 kg N, 10 kg P and 120 kg K ha^{-1}. During warm and dry periods the green was irrigated for 10 minutes (6–7 mm water) up to six times per week.

Experimental setup

Three experimental treatments were imposed in factorial combinations, i) root zone composition (described above), ii) use/not use of surfactant, and iii) fungicide (Fig. 1). The non-ionic surfactant, Primer 604 (Aquatrols Corporation, NJ, USA) was applied 5 times during the growing season to 8 lysimeters (*S*) at a rate of 19 L ha^{-1} (the use of trade names in this paper does not imply endorsement of a product). The surfactant was diluted to 750 L ha^{-1} aqueous solution and applied with an experimental plot sprayer. The remaining lysimeters (*NS*) did not receive any surfactant. Primer 604 was chosen because it is the most widely used surfactant on golf greens in Scandinavia. Fungicide treatments were carried out twice in spring/early summer and once in late autumn according to recommendations by the manufacturer for the control of take-all (*Gauemannomyces graminis*) and snow mould (*Microdochium nivale* and *Typhula* sp.), respectively. The lysimeters were treated either with iprodione, *IPR*, (1.5 kg a.i. ha^{-1}, Rovral 75 WG) or azoxystrobin, *AZO*, (0.6 kg a.i. ha^{-1}, Amistar Duo) and propiconazole, *PRO*, (0.375 kg a.i. ha^{-1}, Amistar Duo). Both products were applied in 250 L ha^{-1} aqueous solution. Compound properties are summarized in Table 2. These fungicides are widely used on golf greens in Scandinavia. Furthermore, *IPR* has been previously detected in drainage water from golf greens in Norway (Ludvigsen et al., 2004) and Sweden (Strömqvist and Jarvis, 2005). Iprodion and *PRO* have also been frequently detected in surface water samples taken from golf courses in the USA (Cohen et al, 1999).

After fungicide application, drainage water was collected from each lysimeter in steel tanks during a period of 2–4 weeks depending on the amounts of rainfall and irrigation (Table 3). Samples for fungicide analysis were taken after thorough mixing of the water in each tank. Fungicide concentrations were measured at Bioforsk Pesticide Laboratory using the M60 Multivann method (Holen and Christiansen, 2006). The sampling scheme is summarized in Fig. 2.

Physical and hydraulic properties

Undisturbed cylinder samples (37 mm high, 58 mm diameter) were taken on 1 September 2006 after the last surfactant application. One cylinder was sampled from the depth 2.0–5.7 cm (just under the thatch layer) and one from 15.0–18.7 cm in each lysimeter. The samples were analyzed for bulk density, total porosity and air- and water filled porosity at the pressure potential -2 kPa. Air permeability was determined according to Green and Fordham (1975) and saturated hydraulic conductivity was estimated from air permeability according to Riley (1996).

Soil water contents

On 13 September 2006, gravimetric soil water contents at the depths 0–2, 2–4, 4–6, 6–10, 10–15, 15–20, 20–25 and 25–30 cm were determined in samples taken with an auger at three random locations in each lysimeter. On 20 September, another set of five soil water content samples were taken from the 2–5 cm depth in each lysimeter. Soil water contents at sampling were also determined in the undisturbed cylinder samples taken on 1 September (see previous paragraph).

Water drop penetration time tests

The persistence of the soil water repellency was measured with the water drop penetration time (WDPT) test (e.g. Dekker and Jungerius, 1990). On 20 September 2006 and on 24 April 2007, two soil samples per lysimeter were taken with a spade sampler which removes a slice of soil, 11 cm wide, to a depth of 10 cm. After 48 h of air drying in the laboratory at 20 °C and 60% relative humidity, three drops of water were placed at 1, 2, 3, 5 and 10 cm depth on the surface of the samples and the time until the drops had infiltrated was measured. Each WDPT was treated as an individual measurement in the statistical analysis. Since the WDPT test was done on dry samples the results reflect potential soil water repellency rather than actual repellency (Dekker and Ritsema, 1994). Potential soil water repellency is a suitable measure of the susceptibility of a soil to water repellency since it is less dependent on the soil moisture content at the time of sampling (Dekker and Ritsema, 1994). According to the classification scheme proposed by Dekker and Jungerius (1990) a soil is considered wettable if drop infiltration is immediate, non-repellent if WDPT<5 s, slightly water repellent if 5s<WTPT<60 s, and strongly water repellent if 60 s<WTPT<600 s.

Infiltrometer measurements

We used tension infiltrometers to measure the actual field soil water repellency. This approach is based on the observation that ethanol infiltration is unaffected by the hydrophobic organic coatings responsible for soil water repellency (Letey et al., 1962). Hence, differences in infiltration rates between water and ethanol can provide information on the degree of soil water repellency. The infiltration rate is a function of both the pressure head imposed by the infiltrometer, h (m), and the properties of the wetting liquid. To account for the differences between water and ethanol we calculated a scaled pressure head (m^{-1}) according to Tillman et al. (1989):

$$h^* = \rho g h / \sigma \qquad (1)$$

where ρ (kg m^{-3}) is the liquid density, g (m s^{-2}) is the acceleration due to gravity and, σ (N m^{-1}) is the surface tension. We used tension infiltrometers with 14 cm diameter infiltrating surfaces. The pressure head at the infiltrating surface was set to -3 cm for water and -1.2 cm for ethanol (Eq. 1, based on densities and surface tensions at 18 °C). Measurements were made on 20 and 21 September with 8 replicates for water and 4 to 5 replicates for ethanol. Water and ethanol infiltration were measured at different locations within each lysimeter. Since the within plot variation might be significant it was not considered meaningful to calculate *R*-values for individual lysimeters.

Under the assumptions outlined by Ankeny et al. (1991) the steady state infiltration rate from a circular source is proportional to the hydraulic conductivity. However, the hydraulic conductivity in Darcy's law is a property of both the porous medium and the liquid. All other things being equal, the flow rate will be inversely proportional to the viscosity, η (N s m^{-2}), of the liquid (i.e. the hydraulic conductivity is inversely proportional to the viscosity). To enable a comparison between the steady state infiltration rate for water, i_w (m s^{-1}), and ethanol, i_e (m s^{-1}), we defined $i_e^* = i_e \cdot \eta_e / \eta_w$ (where η_e/η_w=1.2, viscosities at 18 °C). Following the ideas by Tillman et al. (1989) we introduced the water repellency index, $R = i_e^* / i_w$. The *R*-value will be 1 for a wettable soil and larger than 1 for a repellent soil. It should be noted that this index is based on steady state infiltration rates whereas the index proposed by Tillman et al. (1989) was based on sorptivity measurements. We chose to use steady state infiltration rates because they are less dependent on initial soil water contents. It is therefore possible to compare treatments which might have different initial water contents. The disadvantage of using steady state infiltration rates is that soil water repellency might deteriorate during infiltration resulting in increasing rates with time (Clothier et al., 2000). However, this effect was not apparent in our infiltration measurements.

Turf quality

Although the main focus of the paper is on water repellency, measurement of turf quality was included to put any environmental effects into context in relation to possible effects on playing quality. Turfgrass quality (visual merit) and shoot density was graded on a scale from 1 to 9 where 9 is best, at approximately monthly intervals (Morris, 2006). Percent of plot affected by disease was also estimated throughout the growing season of 2006 and after snow melt in spring 2007.

Statistical analysis

The experimental data were analyzed using the SAS Release 9.1 software package (SAS Institute, Cary, NC). We used the analysis of variance (ANOVA) tool for all data except for the non-normal distributed WDPT data. For this data we used the Kruskal-Wallis test which is a non-parametric alternative to ANOVA. Probability levels are indicated in the tables. Throughout this paper, the term 'significant' always refers to $P<0.05$, and 'tendencies' to $0.05<P<0.10$). For the *AZO*/*PRO* treated lysimeters we used the average relative leaching of the two fungicides.

RESULTS AND DISCUSSION

Physical and hydraulic properties

The effects of root zone composition on physical and hydraulic properties are presented in Table 4. All properties, except saturated hydraulic conductivity, showed significant treatment effects both at 2–5.7 and 15–18.7 cm depth. The larger organic matter content in the *GM* lysimeters (Table 1) resulted in lower bulk density and air-filled porosity and higher water content at -2 kPa and total porosity compared to the *SS* lysimeters.

Water contents

Results from soil water content measurements are summarized in Tables 5a and 5b. The mean soil water contents were higher in the *GM* than in the *SS* lysimeters for all dates and depths. This is in accordance with the higher water content at -2 kPa (Table 4) which enabled wetter conditions in the *GM* lysimeters. The surfactant treatment significantly increased the water content just below the thatch layer on 1 September and showed a similar tendency for the 0–2 cm thatch layer on 13 September. This is in agreement with Dekker et al. (2005) who found higher water contents in dune sand after treatment with Primer 604. A significant interaction on 1 September (Fig. 3) and a similar tendency on 21 September suggest that the effect of surfactant on the mean soil water content just under the thatch layer was more pronounced on *SS* than *GM* lysimeters.

Straight sand lysimeters generally had larger coefficients of variation in soil water content than *GM* lysimeters (Table 5b). This less uniform wetting of the *SS* lysimeters is an indication of preferential finger flow due to stronger water repellency. As a main effect, the surfactant treatment decreased the variation in soil water content at 6–10 cm depth on 13 September and showed a similar tendency at 4–6 cm depth on the same date and at 2–5 cm depth on 21 September. However, on 13 September, there were also significant interactions showing that the decrease in variability in soil water content at 6–10 and 10–15 cm depth only occurred on *SS* root zones (not shown). All in all, the data show that surfactant treatment has a greater potential to improve the infiltration uniformity below the thatch layer on *SS* than on *GM* root zones.

Water repellency

Treatment effects on WDPT are presented in Table 6. Water drop penetration times generally decreased with depth from average values representing strong water repellency at 1 and 2 cm depth to non-repellent at 10 cm depth. This means that close to the surface the greens had a strong potential for water repellency if allowed to dry. Straight sand lysimeters had longer WDPTs at 5 cm depth on 20 September 2006 and at 2 cm depth on 24 April 2007 compared to *GM* lysimeters indicating that *SS* lysimeters may have a stronger potential for water repellency. Surfactant treatment reduced water repellency close to the soil surface. There were no significant differences below the 3 cm depth where repellency was generally weaker. Even though the last surfactant treatment was on 30 August 2006, *S* plots were still less water repellent than *NS* plots at 1 cm depth in the spring of 2007. A stronger effect of surfactant treatment close to the soil surface was also reported by Dekker et al. (2005), which they attributed to adsorption of the surfactant in the organic rich surface layer. Cisar et al. (2000) and Kostka (2000) also reported a reduction in the potential soil water repellency of surfactant-treated golf turf.

The results from measurements of actual soil water repellency by tension infiltrometers are summarized in Table 7. Regardless of treatment, repellency indices were larger than 1, showing that all lysimeters were to some extent water repellent. Jarvis et al. (2007) reported an R-value of 15 based on steady state infiltration rates for a clay soil under pasture. Since all other studies that we are aware of were based on sorptivity measurements we cannot directly compare the *R*-values presented in Table 7 to other values reported in the literature. Our infiltration tests were conducted on 20–21 September when the greens were rather wet (Table 5a). The actual soil water repellency measured in the field was therefore expected to be lower than the potential soil water repellency indicated by the WDPT test. Despite this, surfactant treatment resulted in almost 3 times larger steady state infiltration rates for water implying that a larger fraction of the soil contributed to the infiltration. Compared to the WDPT tests, the infiltrometer measurements give information at a larger scale and therefore provide information that might be more relevant for leaching.

Turf quality

A summary of the visual observations of turf quality, shoot density and percentage of area affected by disease is presented in Table 8. Green mix plots had significantly better turf quality than *SS* plots during the autumn period of 2006 and the spring of 2007. During the autumn period, the occurrence of disease was also lower in *GM* plots. Surfactant treated plots had better turf quality for *SS* lysimeters on 1 July and 1 August, but the effect was not significant when averaged over the whole summer period. In the autumn, there tended to be an opposite effect, as the surfactant increased disease occurrence and reduced turf quality on *SS* lysimeters, while it had no effect on *GM* lysimeters (data not shown). Adverse effects of the surfactant treatment were significant in the spring of 2007 when the percentage of plots affected by disease was twice as high in *S* plots. The increase in water content of the thatch layer (Fig. 3) may have aggravated disease occurrence on *SS* lysimeters. However, the even higher water content (Table 5a) in *GM* plots did not result in larger areas with fungal diseases. This may be because the garden compost contains a different microbial community which may be antagonistic to fungal diseases (Boulter et al., 2000). Other studies (Cisar et al., 2000; Kostka, 2000) have reported positive effects of surfactant treatment on turf quality and the occurrence of LDS in drought periods.

The *AZO/PRO* treatment resulted in better turf quality in the autumn of 2006 and in the spring of 2007 and a smaller percentage affected by disease in the autumn of 2006 than the *IPR* treatment. There was also a significant *root zone x fungicide* interaction, as disease occurrence was especially prevalent on *SS* lysimeters that had not been sprayed with *AZO/PRO* (Fig. 4). The main disease diagnosed in autumn 2006 was Leptosphaerulina leaf blight (*Leptosphaerulina australis*). This is a disease which primarily attacks slowly growing and weakened turf (Tani and Beard, 1997), as was the case on *SS* lysimeters. There were no significant differences in shoot densities.

Fungicide leaching

Treatment effects on drain discharge and accumulated relative leaching for the whole experimental period are presented in Table 9. We did not detect any significant differences in drain discharge. For the *GM* lysimeters, *PRO* was not detected in any samples and *IPR* and *AZO* were detected in only 1 of the 16 samples each. There are probably two main reasons for the almost total elimination of leaching from the *GM* lysimeters. Firstly, the high organic matter content facilitated strong sorption of the fungicides. Secondly, degradation of the fungicides may have been faster in *GM* lysimeters due to higher microbial activity (Cole et al., 1995). Strömqvist and Jarvis (2005) also reported significant effects of organic matter content on the leaching of *IPR* from golf greens.

For *SS* lysimeters, fungicides were detected in all samples. This is a strong indication of preferential flow considering the sorption strength of the fungicides (Table 2) and the small accumulated drainage amounts (Table 3) compared to the pore volumes of the lysimeters. Accumulated leaching for the whole experimental period was larger from *NS* lysimeters compared to *S* lysimeters for all three fungicides (Fig. 5). This strongly suggests that the weaker water repellency in the top layer of the *S* lysimeters (Table 6 and 7) reduced preferential flow and transport of the fungicides. The surfactant treatment led to a more uniform infiltration and hence longer residence times for the fungicides in the biologically active topsoil where microbial degradation took place. There may also be another explanation for the larger fungicide losses from the *NS* lysimeters, as the surfactant itself may have influenced the sorption of the fungicides. Batch experiments have shown that herbicide sorption depends in a complex way on the concentration of non-ionic surfactants present in soil solution (Iglesias-Jiménes et al., 1996; Abu-Zreig et al., 1999). However, considering the consistency in our data, we believe that the reduction in leaching was primarily due to the decrease in preferential flow induced by soil water repellency. This strongly suggests that effective management of soil water repellency would also have beneficial effects on fungicide leaching. Our results are strictly speaking limited to non-ionic surfactants with the same mode of action as Primer 604, but it seems likely that any surfactant which reduces water repellency will also reduce fungicide leaching.

There were no significant differences between the relative leaching of *IPR* and the combination of *AZO* and *PRO* (Table 9). The total accumulated leaching from the *SS* lysimeters (Fig. 5) were smaller for *PRO* than for *IPR* and *AZO* partly because the applied amount was smaller, but also because *PRO* is more strongly sorbed than *IPR* and *AZO* (Table 2).

The accumulated leached amounts shown in Table 9 are underestimations of the total losses during the experimental period because some leaching most likely occurred during the times between sampling and the start of the next fungicide application. This contribution may be significant, especially for *AZO* and *PRO* considering their longer degradation half-lives (Table 2).

The average concentrations for each collection period for the *SS* lysimeters split by surfactant treatment are presented in Fig. 6. The highest leachate concentrations were generally recorded after the first of the three applications. This may be due to microbial adaptation which has been shown to have a strong effect on degradation rates for *IPR* (Walker et al., 1986). The possibilities to draw definitive conclusions from the temporal patterns of fungicide concentrations were hampered by different climatic conditions and different lengths of sampling periods (Table 3). However, it is clear that all three fungicides persisted in the system until the spring following the last application. Maximum concentrations of the fungicides were 6.8, 8.6 and 1.7 μg L^{-1} for *IPR*, *AZO* and *PRO* respectively. These concentrations were all recorded in discharge from *NS* treated *SS* lysimeters. Peak concentrations were probably even higher since our values are averaged over multiple leaching events. The maximum concentrations for all three fungicides exceeded the Norwegian guideline values based on predicted no effect (PNEC) values ($IPR_{\text{no effect}}$=3.4, $AZO_{\text{no effect}}$=0.9 and $PRO_{\text{no effect}}$=0.13 μg L^{-1}; Ludvigsen and Lode, 2005). All three maximum concentrations were also well above the EU limit of 0.1 μg L^{-1} for drinking water (Council of the European Union, 1997). This shows that applying fungicides on green constructions with very low organic matter content is not acceptable from an environmental point of view. The fact that the turf on the *SS* lysimeter greens used in our experiments was three years old and had accumulated 14 mm of thatch did not affect this conclusion, although our results show that fungicide leaching on such soils can be reduced substantially by regular use of surfactants.

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REFERENCES

Abu-Zreig, M., R.P. Rudra, W.T. Dickinson, and L.J. Evans. 1999. Effect of surfactants on sorption of atrazine by soil. J. Contam. Hydrol. 36:249–263.

Ankeny, M.D., M. Ahmed, T.C. Kaspar, and R. Horton. 1991. Simple field method for determining unsaturated hydraulic conductivity. Soil Sci. Soc. Am. J. 55:467–470.

Bauters, T.W.J., D.A. DiCarlo, T.S. Steenhuis, and J.Y. Parlange. 1998. Preferential flow in water-repellent sands. Soil Sci. Soc. Am. J. 62:1185–1190.

Boulter, J. I., G.J. Boland, and J.T. Trevors. 2000. Compost: A study of the development process and end-product potential for suppression of turfgrass disease. World J. Microb. Biotech. 16:115–134.

Bromilow, R.H., A.A. Evans, and P.H. Nicholls. 1999. Factors affecting degradation rates of five triazole fungicides in two soil types: 2. Field studies. Pestic. Sci. 55:1135–1142.

Cisar, J.L., K.E. Williams, H.E. Vivas, and J.J. Haydu. 2000. The occurrence and alleviation by surfactants of soil-water repellency on sand-based turfgrass systems. J. Hydrol. 231/232:352–358.

Clothier, B.E., I. Vogeler, and G.N. Magesan. 2000. The breakdown of water repellency and solute transport through a hydrophobic soil. J. Hydrol. 231/232:255–264.

Cohen, S., A. Svrjcek, T. Durborow, and N.L. Barnes. 1999. Water quality impacts by golf courses. J. Environ. Qual. 28:798–809.

Cole, M. A., L. Zhang, and X. Liu. 1995. Remediation of pesticide contaminated soil by planting and compost addition. Compost Sci. Utilization 3:20–30.

Council of the European Union. 1997. Proposal for a council directive establishing annexe VI to directive 91/414/EEC concerning the placement of plant protection products on the market. Official J. Eur. Communities C240:1–23.

Dekker, L.W., and P.D. Jungerius. 1990. Water repellency in the dunes with special reference to the Netherlands. Catena Suppl. 18:173–183.

Dekker, L.W., and C.J. Ritsema. 1994. How water moves in a water repellent sandy soil .1. Potential and actual water repellency. Water Resour. Res. 30:2507–2517.

Dekker, L.W., and C.J. Ritsema. 1996. Preferential flow paths in a water repellent clay soil with grass cover. Water Resour. Res. 32:1239–1249.

Dekker, L.W., S.H. Doerr, K. Oostindie, A.K. Ziogas, and C.J. Ritsema. 2001. Water repellency and critical soil water content in a dune sand. Soil Sci. Soc. Am. J. 65:1667–1674.

Dekker, L.W., K. Oostindie, S.J. Kostka, and C.J. Ritsema. 2005. Effects of surfactant treatments on the wettability of a water repellent grass-covered dune sand. Aust. J. Soil Res. 43:383–395.

Doerr, S.H., R.A. Shakesby, and R.P.D. Walsh. 2000. Soil water repellency: Its causes, characteristics and hydro-geomorphological significance. Earth Sci. Rev. 51:33–65.

Doerr, S.H., C.T. Llewellyn, P. Douglas, C.P. Morley, K.A. Mainwaring, C. Haskins, L. Johnsey, C.J. Ritsema, F. Stagnitti, G. Allinson, A.J.D. Ferreira, J.J. Keizer, A.K. Ziogas, and J. Diamantis. 2005. Extraction of compounds associated with water repellency in sandy soils of different origin. Aust. J. Soil Res. 43:225–237.

Doerr, S.H., R.A. Shakesby, L.W. Dekker, and C.J. Ritsema. 2006. Occurrence, prediction and hydrological effects of water repellency amongst major soil and land-use types in a humid temperate climate. Eur. J. Soil Sci. 57:741–754.

Green, R.D., and S.J. Fordham, 1975. A field method for determining air permeability in soil. MAFF Tech. Bull. 29:273–287.

Hallett, P.D., and I.M. Young. 1999. Changes to water repellence of soil aggregates caused by substrate-induced microbial activity. European. J. Soil Sci. 50:35–40.

Hendrickx, J.M.H., L.W. Dekker, and O.H. Boersma. 1993. Unstable wetting fronts in water-repellent field soils. J. Environ. Qual. 22:109–118.

Holen, B., and A. Christiansen. 2006. Handbook of analytical methods for pesticide residues. Norwegian Institute for Agricultural and Environmental Research, Bioforsk Laboratory, Ås, Norway.

Iglesias-Jiménez, E., M.J. Sanchez-Martin, and M. Sanchez-Camazano. 1996. Pesticide adsorption in a soil-water system in the presence of surfactants. Chemosphere 32:1771–1782.

Jarvis, N.J., Etana, A., and Stagnitti, F. 2007. Water repellency, near-saturated hydraulic conductivity and preferential solute transport in a macroporous clay soil. Geoderma, *In press.*

Kostka, S.J. 2000. Amelioration of water repellency in highly managed soils and the enhancement of turfgrass performance through the systematic application of surfactants. J. Hydrol. 231/232:359–368.

Letey, J., Osborn, J., and R.E. Pelishek. 1962. Measurement of liquid-solid contact angles in soil and sand. Soil Sci. 93:149–153

Ludvigsen, G.H., Vandsemb, S., and O. Lode. 2004. Pesticider i avrenning fra norske golfbaner. Vanni 2:2004.

Ludvigsen, G.H., and O. Lode. 2005. Tap av pesticider fra jordbruksareal - utvikling over tid. Resultater fra Jord- og vannovervåking i landbruket 2004. Jordforsk rapport nr 97/05. Jordforsk Senter for jordfaglig miljøforskning. Ås, Norway.

Morley, C.P., K.A. Mainwaring, S.H. Doerr, P. Douglas, C.T. Llewellyn, and L.W. Dekker. 2005. Organic compounds at different depths in a sandy soil and their role in water repellency. Aust. J. Soil Res. 43:239–249.

Morris, K.N. 2006. A Guide to NTEP Turfgrass Ratings. National Turfgrass Evaluation Program. http://ntep.org/reports/ratings.htm. Accessed 2007/11/30.

Nektarios, P.A., A.M. Petrovic, and T.S. Steenhuis. 2002. Effect of surfactant on fingered flow in laboratory golf greens. Soil Sci. 167:572–579.

Petrovic, A.M., W.C. Barrett, I.M. Larsson-Kovach, C.M. Reid, and D.J. Lisk. 1998. Downward migration of metalaxyl fungicide in creeping bentgrass sand lysimeters as affected by organic waste, peat and zeolite amendments. Chemosphere 37:249–256.

Riley, H., 1996. Estimation of physical properties of cultivated soils in southeast Norway from readily available soil information. Norwegian J. Agric. Sci. Supp. 25:1–51.

Strömqvist, J., and N. Jarvis. 2005. Sorption, degradation and leaching of the fungicide iprodion in a golf green under Scandinavian conditions: Measurements, modelling and risk assessment. Pest Manage. Sci. 61:1168–1178.

Tani, T. and J.B. Beard 1997. Color atlas of turfgrass diseases. John Wiley & Sons, Hoboken, New Jersey.

Thorstensen, C.W., and O. Lode. 2001. Laboratory degradation studies of bentazone, dichlorprop, MCPA, and propiconazole in Norwegian soils. J. Environ. Qual. 30:947–953.

Thorstensen, C.W., O. Lode, O.M. Eklo, and, A. Christiansen. 2001. Sorption of bentazone, dichlorprop, MCPA, and propiconazole in reference soils from Norway. J. Environ. Qual. 30:2046-2052.

Tillman, R.W., D.R. Scotter, M.G. Wallis, and B.E. Clothier. 1989. Water-repellency and its measurement by using intrinsic sorptivity. Aust. J. Soil Res. 27:637–644.

US Golf Association. 2004. http://www.usga.org/turf/course_construction/green_articles/putting_green_guidelines.html. Accessed 2007/06/11.

van Beinum, W., S. Beulke, and C.D. Brown. 2005. Pesticide sorption and diffusion in natural clay loam aggregates. J. Agric. Food Chem. 53:9146–9154.

van Beinum, W., S. Beulke, C. Fryer, and C. Brown. 2006. Lysimeter experiment to investigate the potential influence of diffusion-limited sorption on pesticide availability for leaching. J. Agric. Food Chem. 54:9152–9159.

van Dam, J.C., J.M.H. Hendrickx, H.C. van Ommen, M.H. Bannink, M.T. van Genuchten, and L.W. Dekker. 1990. Water and solute movement in a course-textured water-repellent field soil. J. Hydrol. 120:359–379.

Walker, A., P.A. Brown, and A.R. Entwistle. 1986. Enhanced degradation of iprodione and vinclozolin in soil. Pestic. Sci. 17:183–193.

White, N.A., P.D. Hallett, D. Feeney, J.W. Palfreyman, and K. Ritz. 2000. Changes to water repellence of soil caused by the growth of white-rot fungi: studies using a novel microcosm system. FEMS Microbiol. Lett. 184:73–77.

Wu, L., G. Liu, M.V. Yates, R.L. Green, P. Pacheco, J. Gan, and S.R. Yates. 2002. Environmental fate of metalaxyl and chlorothalonil applied to a bentgrass putting green under southern California climatic conditions. Pest Manage. Sci. 58:335–342.

Table 1. Results of chemical soil analyses for samples taken at the 0–30 cm depth. Data for pH, ammonium-lactate (AL) extractable P, K, Mg, Ca, and ignition loss are from May 2004 (n=3) while cation exchange capacity (CEC) values are means of samples from May 2004 and November 2005 (n=2).

Root zone	pH (H_2O)	P-AL	K-AL	Mg-AL	Ca-AL	Ignition loss	CEC
		mg kg^{-1}				%	$cmol_c$ kg^{-1}
Straight Sand	66	13	21	21	170	0.4	0.4
Green Mix	75	56	69	88	1730	2.1	4.8
P-value	<0.05	<0.001	<0.05	<0.01	<0.01	<0.001	<0.05

Table 2. Root zone physical properties in undisturbed cylinder samples taken on 1 September 2006 (n=8).

	Straight sand	Green Mix	*P*-value
2.0–5.7 cm depth (just under thatch layer)			
Bulk density, Mg m^{-3}	1.61	1.40	<0.001
Total porosity, %	34.9	40.7	<0.05
†Air filled porosity, %	24.3	16.2	<0.001
†Volumetric water content, %	10.6	24.5	<0.001
Saturated hydraulic conductivity, mm h^{-1}	151	132	>0.10
15.0–18.7 cm depth			
Bulk density, Mg m^{-3}	1.55	1.41	<0.001
Total porosity, %	35.0	40.5	<0.001
†Air filled porosity, %	28.5	23.9	<0.001
†Volumetric water content, %	6.5	16.6	<0.001
Saturated hydraulic conductivity, mm h^{-1}	237	202	<0.10

† At -2 kPa.

Table 2. Fungicide properties.

Fungicide	Adsorption†	Degradation half-lives	Soil
Azoxystrobin	K_f=11.2 $mg^{1-1/n}$ kg^{-1} $L^{1/n}$ and 1/*n*=0.607 (van Beinum et al., 2005)	152 d (van Beinum et al., 2006) §	clay loam
Propiconazole	K_f=27 $mg^{1-1/n}$ kg^{-1} $L^{1/n}$ and 1/*n*=0.88 (Thorstensen et al., 2001)	137 d (Thorstensen and Lode, 2001) ‡	fine sandy loam
	K_f=36 $mg^{1-1/n}$ kg^{-1} $L^{1/n}$ and 1/*n*=0.81 (Thorstensen et al., 2001)	210 d (Thorstensen and Lode, 2001) ‡	loam
	K_d=5.87 L kg^{-1} (Bromilow et al., 1999)	200 d (Bromilow et al., 1999) ¶	clay loam
	K_d=6.9 L kg^{-1} (Bromilow et al., 1999)	200 d (Bromilow et al., 1999) ¶	sandy loam

† K_d, linear adsorption constant; K_f, Freundlich adsorption constant; 1/*n*, Freundlich exponent.
‡ Laboratory incubation experiments at 20° C.
§ Laboratory experiments at 15°C on undisturbed lysimeters.
¶ Field experiments.

Table 3. Dates of the three fungicide applications and periods of drainage water sampling. Corresponding meteorological data are from Landvik weather station, about 200 m from the experimental field.

Date of fungicide application	Drainage water sampling	Mean air temp.	Mean soil temp.	Cumulative rainfall	Cumulative pan evaporation	Cumulative drainage
		°C			mm	
7 June 2007	7 June – 21 June 2007					
28 Aug. 2007	28 Aug. – 24 Sep. 2007					
17 Oct. 2007	17 Oct. – 1 Nov. 2007					

Table 5a. Effects of root zone composition and surfactant on mean gravimetric soil water content in various soil layers on three occasions in September 2006.

	Gravimetric soil water content										
	1 September		13 September								21 September
	2.0–5.7 cm	15–18.7 cm	0–2 cm	2–4 cm	4–6 cm	6–10 cm	10–15 cm	15–20 cm	20–25 cm	25–30 cm	2–5 cm
	%										
Root zone											
Straight sand	4.1	5.4	35.1	6.0	4.2	4.2	4.9	6.0	7.2	9.0	13
Green Mix	16.5	13.8	65.0	17.0	13.1	13.1	13.6	14.0	15.4	18.0	31
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Surfactant											
None	8.9	9.5	45.9	11.5	8.6	8.7	9.4	10	11.4	13.5	21
Primer 604	11.7	9.8	54.2	11.4	8.6	8.5	9.1	10	11.2	13.4	23
P-value	<0.05	>0.1	<0.1	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1
Interaction											
Root zone x Surfactant	<0.05	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1	<0.1

Table 5b. Effects of root zone composition and surfactant on the coefficient of variation in gravimetric soil water content in various soil layers on two occasions in September 2006. Five samples were analyzed per plot on 13 September and three samples per plot on 21 September.

	Coefficient of variation in gravimetric soil water content								
	13 September								21 September
	0–2 cm	2–4 cm	4–6 cm	6–10 cm	10–15 cm	15–20 cm	20–25 cm	25–30 cm	2–5 cm
	%								
Root zone									
Straight sand	26	32	18	11	8	11	8	11	27
Green Mix	14	16	8	4	4	3	4	7	13
P-value	>0.1	<0.05	<0.05	<0.05	<0.01	<0.1	<0.05	>0.1	<0.05
Surfactant									
None	19	23	17	10	7	5	6	7	25
Primer 604	21	24	9	5	6	9	6	11	14
P-value	>0.1	>0.1	<0.1	<0.05	>0.1	>0.1	>0.1	>0.1	<0.1
Interaction									
Root zone x Surfactant	>0.1	>0.1	>0.1	<0.05	<0.01	>0.1	>0.1	>0.1	>0.1

Table 6. Effects of root zone composition and surfactant on water drop penetration times at various soil depths. P-values were calculated using the non-parametric Kruskal-Wallis test.

	Water drop penetration time									
	20 September 2006					24 April 2007				
	1 cm	2 cm	3 cm	5 cm	10 cm	1 cm	2 cm	3 cm	5 cm	10 cm
	s									
Root zone										
Straight sand	207	669	20	9	2	317	660	364	45	0.6
Green Mix	267	54	15	3	2	107	32	18	4	0.3
P-value	>0.1	>0.1	>0.1	<0.05	>0.1	>0.1	<0.05	>0.1	>0.1	>0.1
Surfactant										
None	451	703	24	6	2	415	680	365	43	0.9
Primer 604	23	19	11	7	2	10	10	16	6	0
P-value	<0.001	<0.01	<0.05	>0.1	>0.1	<0.001	<0.01	<0.05	>0.1	>0.1

Table 7. Effects of root zone composition and surfactant on steady state infiltration rates (mm h^{-1}) and repellency index.

	Infiltration rate		Repellency index
	Water	Ethanol	
	mm h^{-1}		
Root zone			
Straight sand	24.9	39.0	1.9
Green Mix	23.7	37.3	1.9
P-value	>0.10	>0.10	
Surfactant			
None	12.9	35.2	3.3
Primer 604	35.7	40.9	1.4
P-value	<0.001	>0.10	
Interactions			
Root zone x Surfactant	>0.10	>0.10	

Table 8. Effects of root zone composition, surfactant and fungicide on turf quality, shoot density and percent of plot affected by disease. Turf quality and shoot density was visually graded on a scale from 1 to 9 where 9 is best.

	Turf quality				Shoot density	Area affected by disease	
	Whole season, -06	20 June–10 Sep, -06	10 Sep–8 Nov, -06	24 Apr -07	Whole season, -06	25 Aug–8 Nov, -06	30 Mar–11 Apr -07
						%	
Root zone							
Straight sand	5.2	5.7	4.5	3.0	5.4	3	55
Green Mix	6.1	6.3	5.7	5.1	6.2	1	41
P-value	<0.1	>0.1	<0.05	<0.001	<0.1	<0.001	<0.1
Surfactant							
None	5.5	5.8	5.1	4.0	5.6	2	31
Primer 604	5.8	6.3	5.1	4.1	5.9	3	65
P-value	>0.1	>0.1	>0.1	>0.1	>0.1	<0.1	<0.01
Fungicide							
iprodion	5.1	5.7	4.2	3.7	5.6	4	48
azoxystrobin + propiconazole	6.2	6.3	6.0	4.5	6.0	1	48
P-value	<0.05	>0.1	<0.01	<0.01	>0.1	<0.001	>0.1
Interactions							
Root zone x Surfactant	>0.1	>0.1	<0.1	<0.05	>0.1	<0.1	>0.1
Root zone x Fungicide	>0.1	>0.1	>0.1	<0.1	>0.1	<0.001	>0.1
Fungcide x Surfactant	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1
Three factor	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1	>0.1

Table 9. Accumulated discharge and pesticide leaching during four drainage collection periods.

	Drain discharge	Leaching
	——— mm ———	% of applied
Root zone		
Straight sand	190	0.092
Green Mix	172	0.00004
P-value	>0.10	<0.01
Surfactant		
None	179	0.067
Primer 604	182	0.015
P-value	>0.10	<0.05
Fungicide		
iprodion	179	0.033
azoxystrobin + propiconazole	182	0.051†
P-value	>0.10	>0.10
Interactions		
Root zone x Surfactant	>0.1	<0.05
Root zone x Fungicide	>0.1	>0.1
Fungicide x Surfactant	>0.1	>0.1
Three factor	>0.1	>0.1

† Average for azoxystrobin and propiconazole.

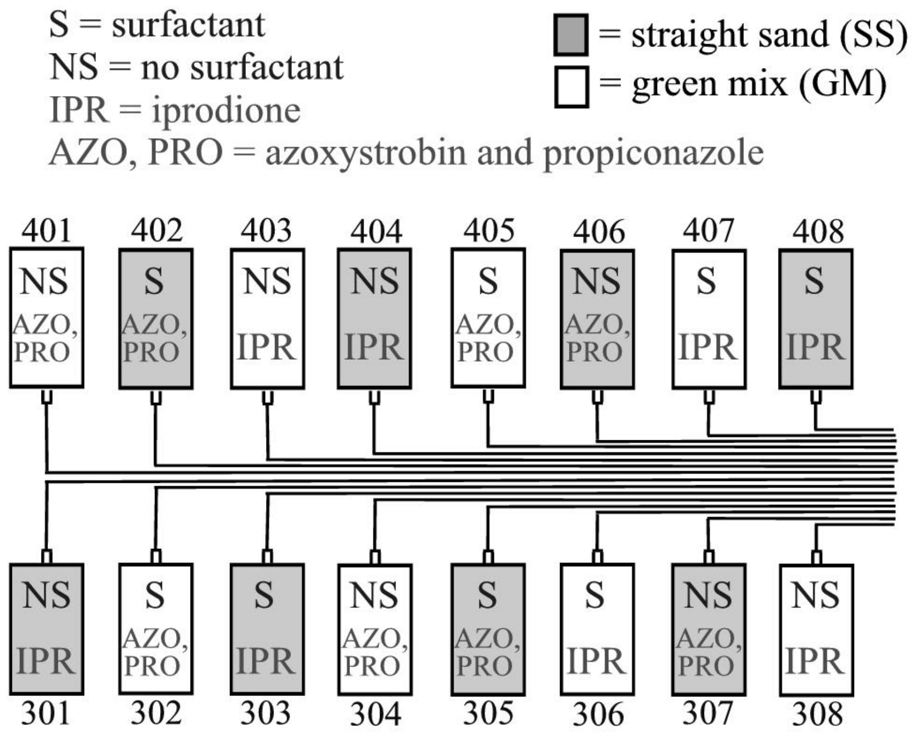

Fig. 1. Schematic representation of the lysimeter facility at Landvik with the treatments *Root zone*, *Surfactant* and *Fungicide* marked.

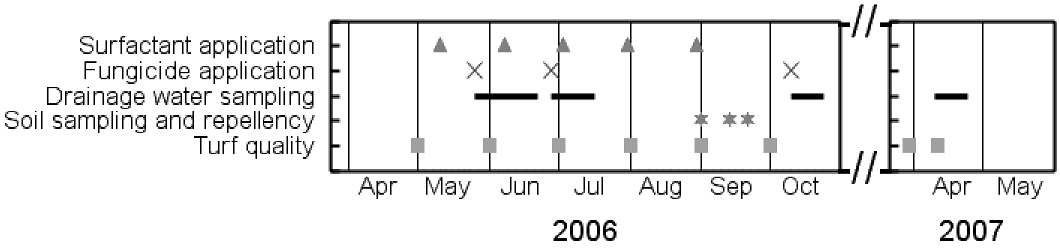

Fig. 2. Management and measurement scheme.

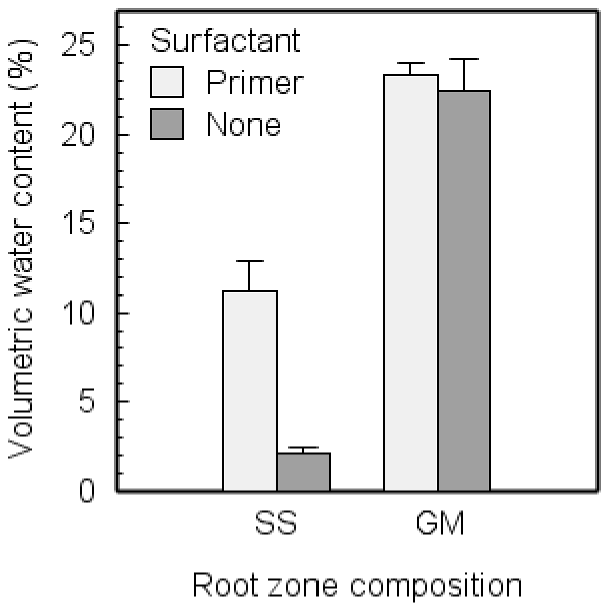

Fig. 3. Effect of surfactant on mean water content in the 2.0–5.7 cm soil layer for the two root zone materials straight sand (*SS*) and green mix (*GM*) on 1 September 2006. Error bars indicate 1 standard error.

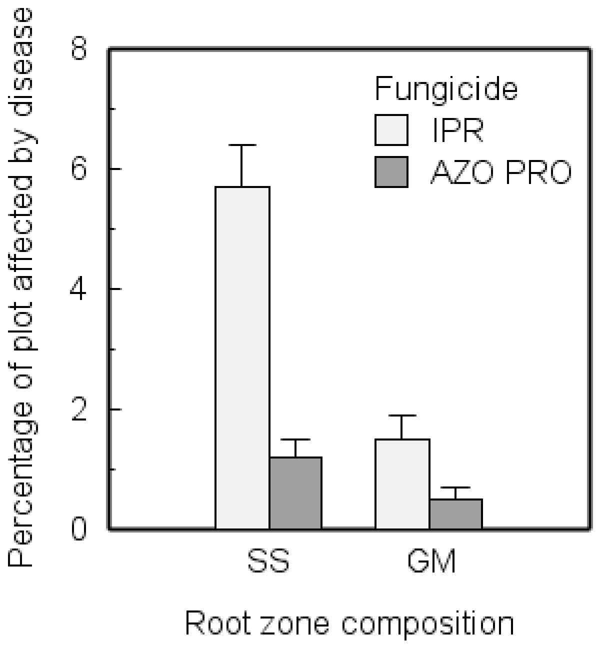

Fig. 4. Effects of fungicide treatments on disease occurrence in autumn 2005 for the two root zone materials straight sand (*SS*) and green mix (*GM*). Mean of lysimeters with and without surfactant. Error bars indicate 1 standard error.

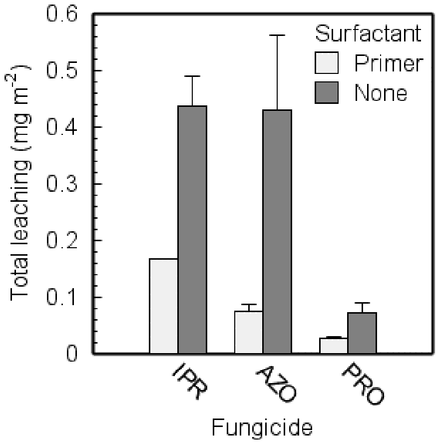

Fig. 5. Effects of the surfactant treatment on accumulated fungicide leaching for the **straight sand** root zone material. *IPR*=iprodion, *AZO*= azoxystrobin and *PRO*=propiconazole. Error bars indicate 1 standard error.

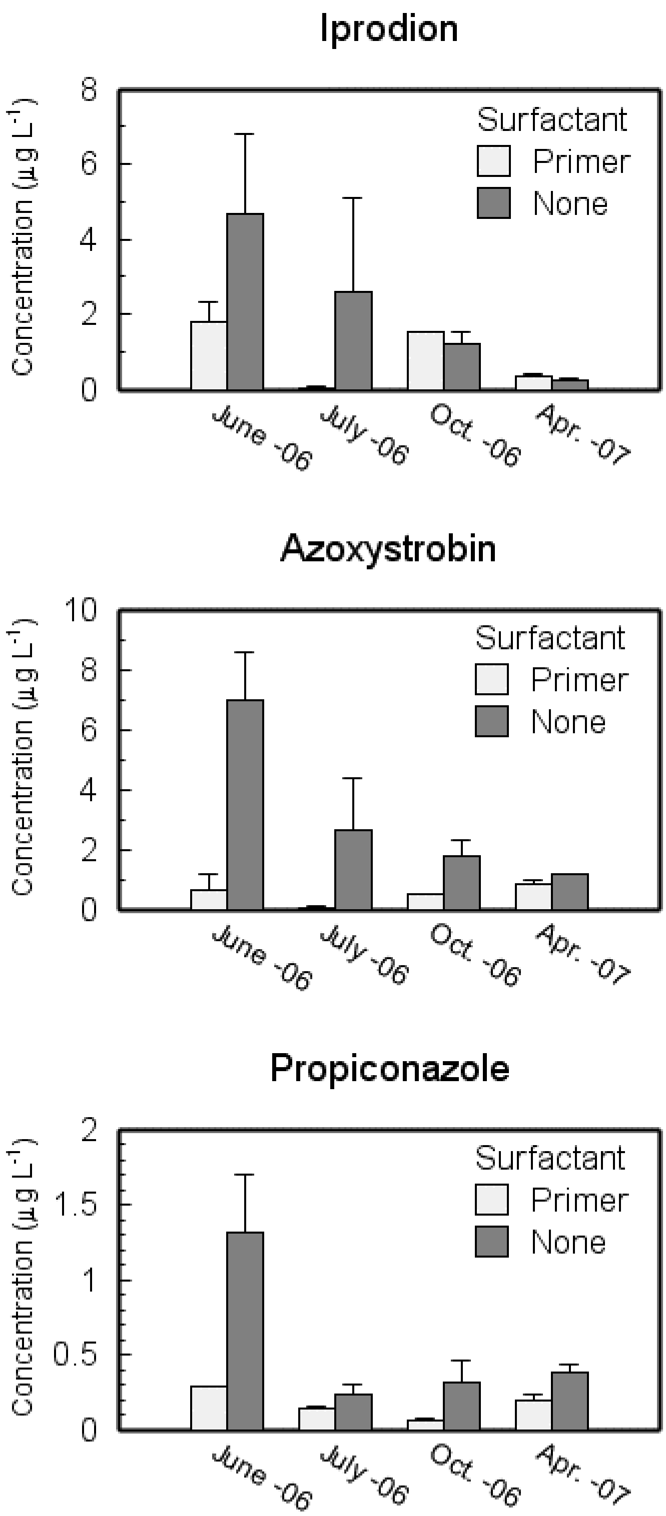

Fig. 6. Effects of the surfactant treatment on fungicide concentrations in drainage water for individual collection periods for the **straight sand** root zone material. Error bars indicate 1 standard error.