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Risks for surface runoff and leaching of fungicides from golf greens varying in rootzone composition and amount of thatch

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SUMMARY

Leaching and surface runoff after fall applications of the fungicides prothioconazole + trifloxystrobin (Delaro® SC 325), boscalid + pyraclostrobin (Signum), fludioxonil (Medallion TL) and their metabolites were studied from 25 Oct. 2016 to 20 March 2017 and from 18 Ovt. 2017 to 6 Apr. 2018. The applications were made on creeping bentgrass (*Agrostis stolonifera*) greens with 5% slope that had been established from seed or sod (25 mm thatch) on USGA-spec. rootzones amended with *Sphagnum* peat or garden compost, both with an ignition loss of 1.0-1.2%. The proportions of the winter precipitation recovered as surface and drainage water varied from 3 and 91 % in 2016/17 to 33 and 55 % in 2017/18 because of differences in temperature, soil freezing, rainfall intensity and ice cover. Detections of the fungicide and their metabolite in drainage water were mostly within the Environmental Risk Limits (ERL) for aquatic organisms. In contrast, many fungicides and metabolites were detected in surface runoff at concentations exceeding ESL values by up to 1000 times. There were small differences in leakage and surface runoff between rootzones amended with compost or peat, but establishment from sod reduced fungicide losses in drainage water compared with direct seeding. The results are discussed in a practical context aiming for reduced environmental risk from fungicide applications against turfgrass winter diseases.

SAMMENDRAG

Utlekking og overflateavrenning etter høstsprøyting av de kjemiske soppmidlene protiokonazol + trifloksystrobin (Delaro® SC 325), boskalid + pyraklostrobin (Signum), fludioksonil (Medallion TL) og deres metabolitter ble studert gjennom vintrene 2016/17 og 2017/18. Krypkveinsgreener med 5% helling var etablert ved såing eller med ferdiggras (25 mm filt) på USGA-sand tilsatt hage/park-kompost eller hvitmosetorv (begge 1.0-1.2 % glødetap). Av den total nedbøren i forsøksperioden ble 3 % gjenfunnet som overflateavrenning og 91% som grøftevann gjennom den første forsøksvinteren. Vinteren etter endret dette seg til 33/55 % på grunn av større temperaturvekslinger, mer tele i jorda, mer nedbør og isdekke. Konsentrasjonen av soppmidler og metabolitter i grøftevannet var store sett innafor miljøfarlighets (MF) - grensene for vannlevende organismer, men i overflatevann ble MF-grensene overskredet inntil 1000 ganger for flere av de undersøkte stoffene. Det var små forskjeller i utlekking eller overflateavrenning mellom rotsoner med torv eller kompost, men bruk av ferdigplen reduserte utlekkinga sammenlikna med såing. Resultatene blir drøfta med vekt på praktiske tiltak for å redusere miljøbelastninga ved sprøyting mot overvintringssopp.

APPROVED / GODKJENT

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Preface

The research project ‘Risks for surface runoff and leaching of fungicides from golf greens varying in rootzone composition and amount of thatch’ was conducted from 1 June 2016 to 1 June 2019 as a collaborative effort between NIBIO’s departments for ‘Urban Greening and Vegetation Ecology’ and ‘Pesticide and Natural Products Chemistry’. The project’s major funding sources were the Norwegian Agriculture Agency’s action plan for more sustainable use of pesticides and the Scandinavian Turfgrass and Environment Reseach Foundation (STERF), a research body set up by the Golf Federations in the five Nordic countries. The German Greenkeeper Association also supported the project on the condition that it should include Signum (boscalid + pyraclostrobin), a fungicide that has an off-label registration in Germany but is not used on Nordic golf courses. Finally the project was connected to the Strategic Institute Program ‘Green cities’ funded by that the Norwegian Ministry of Climate and Environment.

The present report has been written according to STERF’s directions for reports to be published at www.sterf.org by the end of the last project year. It will also serve as an attachment to administrative report to the Norwegian Agriculture Agency by the deadline 1 April 2020.

NIBIO Landvik, 26.11.19

Trygve S Aamlid

Content

1 Introduction

Pesticide use on golf courses and other turfgrass areas is under scrutiny by environmental authorities. According to IPM principles, pesticides shall only be used when other preventative or curative measures do not give sufficient control of weeds, insects or diseases (FAO 2016). One situation where adequate control is difficult to achieve without a minimum use of pesticide is when golf greens are infected by microdochium patch caused by *Microdochium nivale*. This disease affects turfgrass both in autumn and under snow cover during winter and is considered the economically most important disease on Nordic golf courses. A survey in 2014-2015 showed that most greenkeepers spray their greens 1-2 times, but occasionally more (Økland et al. 2018). Within each of the Nordic countries, 3-6 active fungicide ingredients are currently approved for control of this and other diseases.

One of the greatest concerns with pesticide use on golf courses is that the active substances or their metabolites may find their way to streams, rivers, lakes and ground water. EU has a general safety limit of 0.1 $\mu g\ L^{-1}$ of any pesticide in drinking water, and Sweden and Norway have established Environmental Risk Limits (ERLs) for individual pesticide ingredients and their metabolites that must not be exceeded if the surface water shall be safe for aquatic organisms (e.g. Anderson & Kreuger 2011, Stenrød et al. 2014).

About fifteen years ago, the Scandinavian Turfgrass and Environment Research Foundation funded several studies on fungicide fate and environmental risks after application on sand-based greens (see Aamlid 2014 for a review).Two of the most important findings in this research were (1) that the risk for leaching to ground and surface water depended on the chemical properties of the fungicides, particularly their sorption coefficients and half-lives (Larsbo et al. 2008, Aamlid et al. 2009) and (2) that the risk for fungicide leaching could be almost eliminated by increasing the organic matter content in the sand-based rootzone from 1 to 3 % (w/w) (Larsbo & Jarvis 2003, Aamlid et al. 2009).

The early Scandinavian studies were wholly or partly conducted with fungicide that have now been withdrawn from the market, e.g. iprodione and prochloraz. Moreover, none of them included metabolites, i.e. products that an active fungicide ingredient is broken down to, and that may often be equally or even more harmful to the environment than the active ingredient itself. While focusing on ignition loss, these studies also paid little attention to *type* of organic matter in the rootzone. Up to now, the organic amendment most commonly used in sand-based greens has been *Sphagnum* peat. However, within a few years, the use of peat as organic amendment will most likely be forbidden because of the CO2-emissions resulting from the excavation and processing of peat from bogs (Waddington et al. 2002). Sand-based rootzones amended with compost typically have much higher pH values than substrates amended with *Sphagnum* peat, and this may well affect the sorption and risk for leaching of certain fungicides. Rootzones amended with compost will also be expected to have higher microbial activity perhaps leading to faster fungicide degradation than in rootzones amended with peat.

A characteristic feature, especially on sand-based golf greens, is that organic matter accumulates just below the turf canopy. The thatch/mat layer is likely to have a strong impact on the risk for pesticide leaching as is represents a significant barrier to the penetration of pesticides into the soil as well as a potential site for fungicide accumulation (Cisar & Snyder 1996). This is an aspect that was not addressed in the former STERF projects, and reports from the USA have shown variable results as to the efficacy of thatch in reducing pesticide leaching (Sigler et al. 2000). Models developed for organic matter degradation are usually not applicable to thatch (Lickfeldt & Branham 1995), and in some cases it has even been shown that the thatch layer reduces degradation as it prevents pesticides from getting into contact with the underlying rootzone (Sigler et al. 2000, Gardner & Branham 2001)). At least on young greens, this problem will probably be most pronounced when establishing new turfgrass areas with sod. Canaway (1993) observed a much stronger reduction in infiltration rates for sodded than for seeded football pitches during the first year after establishment and this could potentially increase the risk for surface runoff of pesticides. The establishment and especially repair of golf greens with sod is common on Scandinavian golf courses, and the impact on pesticide behaviour of the addition of thatch to young greens requires further investigation.

The former STERF projects were conducted on flat greens where rainfall, excess irrigation and melting water had little or no chance to escape as surface runoff. Golf greens are, however, often undulated to make them more challenging to the players, and although infiltration rates are usually higher than on natural soils, it is a common observation that water moves on the surface to the lower parts on the green. Environmental monitoring in Norwegian agriculture shows that pesticide concentration in runoff during the first rainfall after application are often several orders of magnitudes higher than in drainage water (Bechmann et al. 2014), and similar observations have been reported from turfgrass areas in the United States (Easton et al. 2005, Petrovic & Easton 2005, Kramer et al. 2009, Rice et al. 2010, Borst et al. 2011, Bell & Koh 2011, Slavens & Petrovic 2012, King and Balogh 2013). However, as these studies were conducted during the growing season with turfgrass growing on natural soils, there is an obvious need for more knowledge about fungicide runoff from sand-based greens, particularly in situations where fungicides are sprayed in the late fall before frost and snow cover. This will also become more important in the future as the winter climate becomes less stable due to global warming (IPCC 2014).

The objective of the project reported here were:

1. To clarify the risk for leaching and surface runoff of fungicides currently approved for control of turfgrass winter diseases on golf courses in the Nordic countries and Germany, including metabolites.
2. To compare fungicide leakage and surface runoff from golf greens with *Sphagnum* peat vs. garden compost as organic amendment to the sand-based rootzone.
3. To determine the effect of a thatch/mat layer high in organic matter on turfgrass infiltration rates and thus, the risk for leakage and surface runoff

2 Materials and methods

2.1 Experimental site

This research was conducted in the field lysimter facility at the NIBIO Turfgrass Research Center Landvik, Norway (58°19′N; 8°30′E, 5 m a s.l.) from 25 Oct. 2016 to 20 March 2017 and from 18 Oct. 2017 to 6 April 2018. The facility consisted of 16 stainless steel lysimeters arranged in four blocks. Each lysimeter was 2 m long, 1 m wide and placed in the center of a 3 m x 2 m plot to avoid border effects (Photo 1a,b). Each lysimeter was filled with a 30-40 cm layer of sand above a 10-15-cm gravel layer according to USGA-specifications. The gravel was placed directly on the sloping bottom of the lysimeters, which directed water to the lysimeter outlet and further to a 200 L stainless steel container for collection of drainage water. In preparation for this experiment the lysimeters had been deturfed, more rootzone material added and the surface reshaped to a slope of 5 %. This allowed collection of surface runoff from the 2 m^2 lysimeter surface through a 1 m wide trench leading to a stainless steel container just below each lysimeter (Photo 2b).

Photo 1 a,b. Lysimters at construction in 2003. Photos: Trygve S. Aamlid.

Photo 2 a,b. Remodeling of lysimeters in 2015 to allow for collection of surface water. Photos: Trygve S. Aamlid

2.2 Experimental treatments and design

The experiment had two factors, each with two levels (Photo 3). The four combinations were randomized completely within each block.

Factor 1: Organic amendment to the sand-based (USGA spec.) rootzone:

1. *Sphagnum* peat, ignition loss 1.2%, pH 5.5
2. Garden compost, ignition loss 1.0%, pH 6.5.

Factor 2: Turf age / thatch thickness:

A. Green etsblished by direct seeding
B. Green established using 30 months old sand-based sod, thickness 25 mm

Photo 3: From turfgrass establishment in May 2016. Half of the plots were established using 30 months old sand-based sod of creeping bentgrass. The remaining plots received 30 mm more sand and were seeded using the same creeping bentgrass seed blend as used by the sod grower. In the left photo, the sand amended with garden compost had a darker color than the sand amended with compost. Photos: Trygve S. Aamlid.

2.3 Turfgrass management and fungicide applications

The turfgrass used on both seeded and sodded plots was creeping bentgrass (‘Penn A4’, ‘Penn G2’ and ‘Penn G6’, 1/3 of each variety). The experimental green was maintained according to good greenkeeping practice, including mowing with a walk-behind single mower to 3 mm three times per week and light topdressing once a week for a total height of 5.9 mm sand in 2016 and 6.6 mm sand in 2017. Verticutting was performed four times on seeded plots and six times on sodded plots in 2016. In 2017 all plots were aerated ten times to 15 mm depth using a slicer with knives 40 mm apart. In 2017, the plots were also subjected to wear from a friction wear drum with golf spikes corresponding to 15000 rounds of golf. Fertilizers, partly liquid (Wallco 5-1-4, Orkla Care, Solna, Sweden) and partly granular (Greenmaster Cold Start 11-2.2-4.1 in spring and Greenmaster 14-0-8.3 in summer and fall; ICL Speciality Fertilizers, Ipswich, UK) were applied every two weeks for a total rate of 2.6 kg N / 100 m^2 on seeded plots and 1.8 kg N / 100 m^2 on sodded plots in the grow-in year 2016 and 1.5 kg N / 100 m^2 on all plots in 2017.

The fungicides Delaro® SC 325 (trifloxystrobin 150 g L^{-1} plus protioconazole 175 g L^{-1}; Bayer Crop Science, Leverkusen, Germany; approved for use on golf courses in Norway) and Signum (boscalid 267 g kg^{-1} plus pyraclostrobin 67 g kg^{-1}; BASF, Ludwigshafen, Germany; off-label for use on golf courses in Germany) were sprayed on all plots on 25 Oct. 2016 and 18 Oct. 2017 at a rate of 1.0 L ha^{-1} (Delaro) and 1.5 kg/ha (Signum). The two products were not tank-mixed, but sprayed separately about 2 hours apart. Three weeks later, after mowing had been discontinued for the season, Medallion TL (fludioxonil, 125 g L^{-1}, Syngenta, Base, Switzerland; approved on golf courses in Germany, Finland, Sweden and Norway) was sprayed on 15 Nov. 2016 and 8 Nov. 2017 at a rate of 3.0 L ha^{-1}. The fungicides were applied in a water volume of 250 L ha^{-1} using an experimental backpack plot sprayer (Oxford/LTI) working at 150-200 kPa pressure. The actual application rates were recorded by weighing the tank before and after spraying to ensure that deviations from target rates were within the ±10% limit set by the Norwegian Good Experimental Practice (GEP) Standard.

Photo 4 (left): Profiles of the top layer at the first fungicide application in October 2016; seeded green to the left and sodded green to the right. Right: The same fungicides were applied to all plots using an experimental plot sprayer. Photos: Trygve S. Aamlid

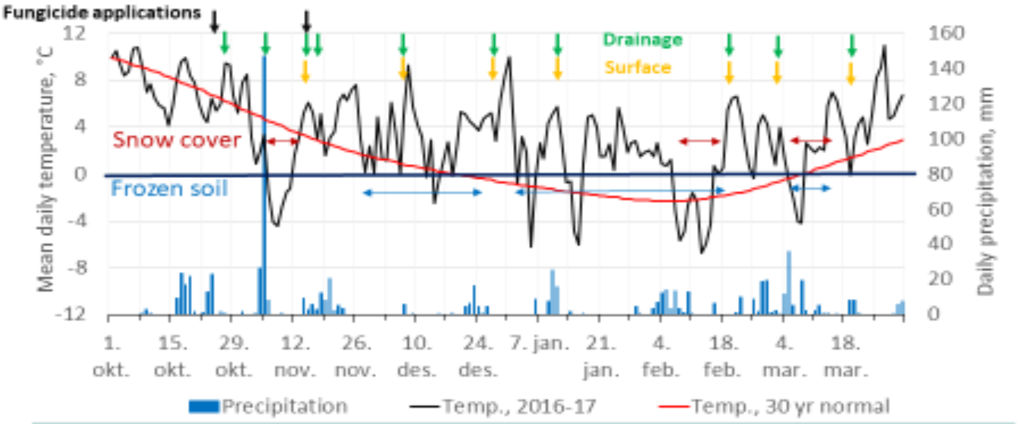
2.4 Weather data

In both years, the experimental period was milder and had more precipitation than the 30 yr (1961-90) reference period (Table 1, Figure 1). The second year 2017-18 (Figure 1b) was colder and implied a longer duration of frozen greens and snow cover, but also more fluctuations between cold and mild weather resulting in more ice formation and surface runoff than in the first year. In the first year, there was a recond-high precipitation of 147 mm d-1, starting as rain and turning into snow, on 5 Nov., ten days after the first fungicide application. In the second year there was also a rather wet period after the first fungicide application on 18 October.

Table 1. Mean temperature, precipitation and total number of days with frozen green surface and snow or ice cover during the experimental periods in 2016-2017 and 2017-18. Monthly temperature and precipitation data have been compared with the 30 reference period 1961-90.

	Temperature mean , °C			Precipitation, mm		
	2016-17	2017-18	30-yr normal	2016-17	2017-18	30-yr normal
October (after start of trial)				4	237	
November	2.7	3.5	3.2	256	157	143
December	3.7	1.7	0.2	44	116	102
January	1.7	0.9	-1.6	65	222	113
February	0.4	-2.0	-1.9	139	143	73
March	3.4	-1.2	1	118	49	85
Mean/ sum, Nov. -March	2.4	0.6	0.2	621	686	516
Mean / sum, trial period	2.3	1.3	-	601	948	516
Days with frozen soil	82	127				
Days with snow or ice cover	30	78				

a) 2016/17



b) 2017/18

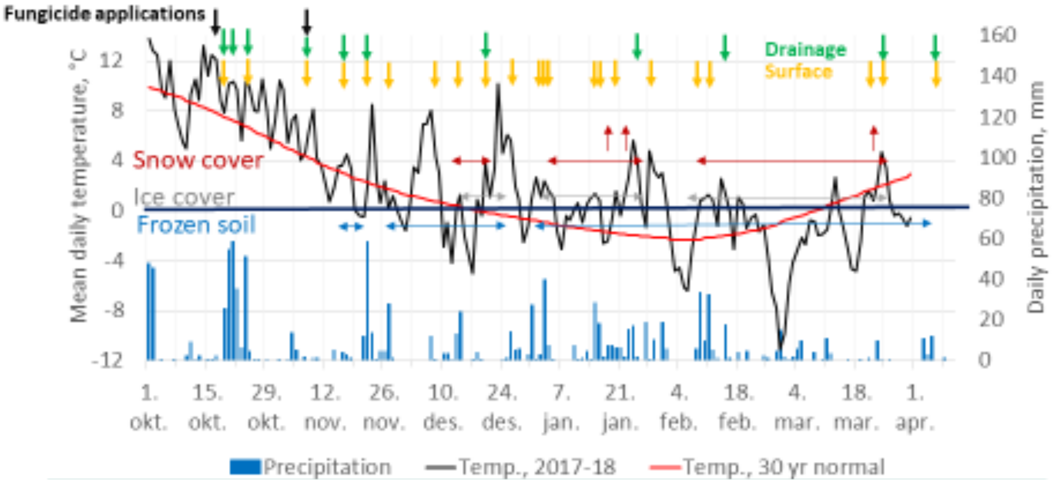


Figure 1. Daily values for temperature and precipitation and days with frozen greens, snow and ice cover during the experimental periods in 2016/17 (top) and 2017/18 (bottom). Black arrows indicate dates for fungicide application and green and yellow arrows dates on which the collectors for drainage water and surface runoff were emptied and samples taken for pesticide analyses. Red arrows in b) indicate dates with snow removal on top of frozen greens.

2.5 Data collection and statistical analyses

One undisturbed soil sample, 37 mm high and 58 mm in diameter, was taken from each of the depths 5-42 mm and 150-187 mm just outside the lysimeter in each plot (not to disturb hydraulic properties within the lysimeter) shortly before the first fungicide application in October 2016. The samples were analyzed for bulk density and air-filled and water-filled porosity at 2.45 kPa suction. On the same date and also at the start of the second experimental period in October 2017, turfgrass infiltration rates were measured using a double ring infiltrometer with 120 and 50 mm diameter of the outer and inner ring, respectively. The infiltrometer was filled to a height of 80 mm and infiltration measured after 3 minutes at two random sites per plot.

Photo 5. Undistubed cylinder samples were taken before the first fungicide application in October 2016. Photo: Trygve S. Aamlid

Two days after each fungicide application, the amount of drainage water and surface water were measured, collectors emptied and the first water samples taken for analyses of the fungicides and their metabolites. Later measurements and sampling of drainage and surface water followed every time the collectors were full and had to be emptied. Because of more precipitation and longer periods with frozen soil, 24 samples of surface water were taken from each plot in 2017/18 as opposed to only 7 samples in 2016/17 (Figure 1). For drainage water, the number of samples per plot was 10 in 2016/17 and 12 in 2017/18. The water samples were analyzed in the laboratory at NIBIO's department of pesticide and natural product chemistry, Ås, Norway.

The concentration of fungicides and their metabolites in drainage water and surface runoff were compared with the Norwegian Environmental Risk Limits (ERL). These values indicate threshold concentrations above which long-term negative effects in aquatic environments might occur. The concentration limits are based on 'No Observed Effects Concentrations (NOEC)'-data from chronic toxicity tests of aquatic organisms, and the calculation includes an assessment factor depending on the quality of these data. This calculation procedure is in accordance with guidelines for environmental quality standards (EQS) for EU's Water framework directive.

The data were analysed using the SAS procedure PROC ANOVA SAS Institute, Cary, NC, USA. Probability levels indicated in the tables are: ***: $P \leq 0.001$; **: $0.001 < P \leq 0.01$; * $0.01 < P \leq 0.05$; (*):$0.05 < P \leq 0.10$; NS: not significant. In the text, the term 'significant' always means $P \leq 0.05$, while effect with $0.05 < P \leq 0.10$ are referred to as 'tendencies' or trends'. Significant differences among treatment combinations were identified using Fisher's LSD at $P \leq 0.05$.

3 Results and discussion

3.1 Rootzone physical properties

The cylinder samples taken in October 2016 showed no effect of type of organic amendment on soil physical properties at 5-42 mm depth. At 150-187 mm depth, the air-filled and total porosity was higher and the soil density lower in rootzones amended with compost than in rootzones amended with peat (Table 2).

Establishing greens by sodding instead of seeding resulted in more air-filled and especially water-filled pores and lower bulk density at 5-42 mm depth. Compared with seeding, sodding also reduced the infiltration capacity by 38 and 54 % when measured 5 and 17 months after turfgrass establishment.

Significant interactions at 150-187 mm depth showed less compaction of the compost-amended rootzone under sodded than under seeded turf. In contrast, there was no effect of seed vs. sod on the physical properties of the underlying rootzone amended with peat (Figure 2).

Table 2. **Main effect of experimental factors on air-filled, water-filled and total porosity and soil density as determined in undisturbed cylinder samples taken from two depths in October 2016, and on infiltration measured using a double-ring infiltrometer in October 2016 and 2017.**

	5- 42 mm depth				150-187 mm depth				Infiltration, mm h^{-1}	
	Porosity, %			Soil density, kg dm-3	Porosity, %			Soil density Kg dm-3	Oct. 2016	Oct. 2017
	Air-filled	Water-filled	Total		Air-filled	Water-filled	Total			
Peat	31.3	24.7	56.0	1.24	33.7	13.8	47.5	1.35	930	596
Compost	29.7	23.8	53.5	1.26	36.6	15.0	51.6	1.30	884	606
Sign.	NS	NS	NS	NS	***	NS	***	***	NS	NS
Seed	28.9	19.3	48.2	1.44	34.4	14.6	48.9	1.34	1123	826
Sod	31.1	29.2	61.3	1.07	35.9	14.2	50.1	1.31	691	376
Sign.	*	***	***	***	NS	NS	*	NS	**	***
Interaction	NS	NS	NS	NS	*	NS	*	*	NS	NS

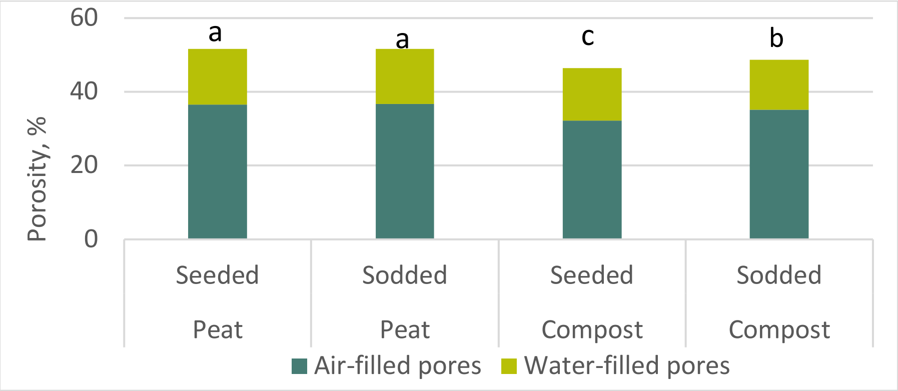


Figure 2. **Effect of combinations of organic amendment to the sand-based rootzine and turfgrass establishment method on air-filled, water-filled and total porosity in cylinder samples taken at 150-185 mm depth in October 2016. Different letters above bars indicate significant difference in air-filled and total porosity (P≤0.05).**

3.2 Collected amount of drainage water and surface runoff

On average for treatments, 549 L m^{-2} (91 % of the total precipitation of 601 mm, Table 1) was collected as drainage water during the experimental period in 2016/17 (Table 3). There was no effect of type of organic matter, but an almost significant (P=0.06) trend to less drainage from sodded than from seeded turf. Only 17 L m^{-2} (3 % of the total precipitation) was collected as surface runoff, most of it during the period with frozen soil from early January to mid-February (Figure 1a). When the greens were unfrozen, there was practically no runoff because of the high infiltration capacity. The record-high rainfall of 147 mm on 5 Nov. 2016 only resulted in 1 L m^{-2} surface runoff (data not shown).

Only 35 mm (6 %) of the total precipitation in 2016-17 was not accounted for as either drainage or surface water. Most of this was probably lost as turfgrass transpiration during the mostly mild winter without snow cover.

Table 3. Main effects of experimental factors on accumulate amount of drainage water and surface runoff L m^{-2}) during the experimental period in 2016/17 and 2016/18.

	2016/17		2017/18	
	Drainage water	Surface runoff	Drainage water	Surface runoff
Peat	560	18	518	315
Compost	538	16	526	305
Sign.	NS	NS	NS	NS
Seeded	571	16	556	308
Sodded	527	18	488	312
Sign.	(*)	NS	*	NS
Interaction	NS	NS	NS	NS

During the second experimental period in 2017/18, the average collection of drainage water and surface runoff amounted to 522 and 310 L m^{-2}, or 55 and 33 % of the total precipitation of 948 mm. The amount of drainage water was significantly lower from sodded than from seeded turf but unaffected by type of organic matter (Table 3). The amount of surface runoff was high from mid-November to early February with peaks on 23 November (high rainfall on frozen greens) and 29 January (mild spell with snow melting over ice-covered greens). The fact that 12 % (114 mm) of the total precipitation in 2017-18 was not collected as either drainage or surface water can partly be ascribed to the fact that the top layer of snow above ice-covered greens was removed on 19 January, 23 January and 23 March in order to avoid overflow in the collectors for surface water.

3.3 Fungicide and metabolite detections during the winter 2016-2017

The maximal concentration of fungicides and their metabolites in drainage water and surface runoff during 2016-17 is shown in Table 4 in comparison with the Norwegian Environmental Risk Limits.

Table 4a shows that fungicide concentrations in drainage water were mostly very low – in most cases one to two orders of magnitude lower than the ERL-value. This confirms our earlier findings (Aamlid 2014) that fungicide applications to golf green represent small environmental risks as long as the entire precipitation infiltrates and the rootzone contains at least 1 % organic matter.

One unexpected finding in Table 4a was the detection of fludioxonil in drainage water from sodded plots on 5 Nov., i.e. before the application of Medallion on 15 Nov. This detection was most likely due to residues as the sod grower had applied fludioxonil in his production of creeping bentgrass sod (Swedish sod grower S. Andersson, pers.comm.).
Except for one detection of the prothioconazole-metabolite desthio on 27 Oct. and one detection of fludioxonil on 15 Nov., the concentration in drainage water was always well below the ERL value. (Table 4a). In contrast, the maximum concentrations of prothioconazole-desthio, trifloxystrobin, boscalid, pyraclostrobin and fludioxonil in surface water were 10-200 times higher than their respective risk limits (Table 4b). The highest surface runoff of boscalid and pyraclostrobin occurred when the heavy rain-and snowfall on 5 Nov. melted about one week later, while the highest concentration of fludioxonil was detected on 7 Dec. when rain fell on partly frozen greens. In both cases, these detections were made about three weeks after application of the respective fungicides. In contrast, the highest concentrations of prothioconazole and pyraclostrobin were detected as late as at the last sampling on 20 March, but these concentrations were barely above the detection limit and too low to have any practical relevance.

Table 4. Maximal detections of various fungicides and their metabolites in a) drainage water and b) surface runoff during the experimental period in 2016-2017.

a) Drainage water

Product / application date	**Active ingredient**	**Active compound or metabolite detected in drainage water**	**Concentation, µg/L**		**Sampling date for maximum concentration**
			Maximum detected	**Norwegian ERL**	
Delaro SC 325, 25.okt	Prothioconazole	Prothioconazole	0.022	0.74	5 Nov.
		Metabolite: Desthio	0.036	0.030	27 Oct.
	Triifloxystrobin	Trifloxystrobin	0.015	0.19	15 Nov.
		Metabolite: Trifloxystrobin-acid	21	64	15 Nov.
Signum, 25.okt	Boscalid	Boscalid	0.058	12.5	27 Oct.
	Pyraclostrobin	Pyraclostrobin	0.022	0.4	15 Nov.
		BF500-6[1]	0.004	-[1]	18 Nov.
Medallion TL, 15.nov	Fludioxonil	Fludioxonil	0.058	0.050	5 Nov.
		Metabolite CGA 192155	7.0	100	28 Dec.

b) Surface runoff

Product / application date	Active ingredient	Active compound or metabolite detected in drainage water	Concentation, µg/L		Sampling date for maximum concentration
			Maximum detected	Norwegian ERL	
Delaro SC 325, 25.okt	Prothioconazole	Prothioconazole	0.0039	0.74	20 Mar.
		Metabolitt: Destio	7.2	0.030	7 Dec.
	Triifloxystrobin	Trifloxystrobin	8.5	0.19	15 Nov.
		Metabolite: Trifloxystrobin-acid	21	64	15 Nov.
Signum, 25.okt	Boscalid	Boscalid	44	12.5	15 Nov.
	Pyraclostrobin	Pyraclostrobin	8.7	0.4	15 Nov.
		Metabolite: BF500-6	0.00075	-[1]	20 Mar.
Medallion TL, 15.nov	Fludioxonil	Fludioxonil	7.9	0.050	7 Dec.
		Metabolite CGA 192155	12.9	100	28 Dec.

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[1] A Norwegian ERL (Environmental Risk Limit) for the pyraklostrobin metabolite BF500-6 has not been determined due to limited data.

Regardless of fungicide, the highest concentrations during the first winter were found in surface water from plots that had been established by sodding on top of a compost-amended rootzone (data not shown).

Despite the fact that drainage and surface water accounted for, in turn, 91 and 3 % , of the total precipitaion, the several fold higher concentration in surface water means that the total fungicide loss to the environment during the 2016/17 winter season was higher for water running off the surface than for water leaking through the rootzone. The only exception to this was the fludioxonil metabolite CGA 192155 for which the mass balance calculation showed more loss in drainage than in surface water.

3.4 Fungicide and metabolite detections during the winter 2017-2018

The maximal concentration of fungicides and their metabolites in drainage water and surface runoff during 2017-18 are shown in Table 5. In this table we have also included information about actual application rates (determined by weighing the sprayer before and after application), total fungicide and metabolite loss in drainage and surface water, and a calculated average concentration of the various fungicides and metabolites during the experimental period.

Table 5. Actual application rates, total loss of various fungicides and their metabolites, and average and maximum concentration in a) drainage and b) surface water during the experimental period in 2017-18.

a) Drainage water

Product / Appli-cation date	**Active ingre-dient**	**Actual appl. rate, mg a.i./m²**	**Active compound or metabolite detected in drainage water**	**Loss in drainage water, 18 Oct.- 6 Apr. mg/m²**	**Concentration, µg/L**			**Samp-ling date for maxi-mum**
					Weighed mean	**Maxi-mum**	**Nor-wegian ERL**	
Delaro SC 325, 18 Oct	Prothio-conazole	19	Prothioconazole	0.0050	0.0095	0.025	0.74	17 Nov.
			Metabolite: Desthio	0.011	0.021	0.16	0.03	25 Mar.
	Trifloxy-strobin	16	Trifloxystrobin	0.00036	0.00070	0.10	0.19	17 Nov.
			Metabolite: Trifloxystrobin–acid	5.9	11	29	64	17 Nov.
Signum, 18 Oct.	Boscalid	41	Boscalid	0.27	0.047	0.59	12.5	25 Mar.
	Pyraclo-strobin	10	Pyraclostrobin	0.00035	0.00069	0.007	0.4	17 Nov.
			Metabolite: BF500-6	0	0	0	-[1]	-
Medallion TL, 8 Nov.	Fludi-oxonil	36	Fludioxonil	0.00165	0.0031	0.092	0.050	17 Nov.
			Metabolite: CGA 192155	0.45	0.86	6.2	100	26 Jan.

b) Surface runoff

Product / Appli-cation date	Active ingre-dient	Actual appl. Rate, mg a.i./m²	Active compound or metabolite detected in surface runoff	Loss in surface water, 18 Oct.- 6 Apr. mg/m²	Concentration, µg/L			Samp-ling date for maxi-mum
					Weighed mean	Maxi-mum	Norw. ERL	
Delaro SC 325, 18 Oct	Prothio-conazole	19	Prothioconazole	0.00017	0.00054	4.1	0.74	20 Oct.
			Metabolite: Desthio	0.023	0.074	15.1	0.03	20 Oct.
	Trifloxy-strobin	16	Trifloxystrobin	0.023	0.076	37.2	0.19	20 Oct.
			Metabolite: Trifloxystrobin–acid	0.034	0.11	16.3	64	20 Oct.
Signum, 18 Oct.	Boscalid	41	Boscalid	0.36	1.20	207.6	12.5	20 Oct.
	Pyraclo-strobin	10	Pyraclostrobin	0.12	0.39	19.3	0.4	20 Oct.
			Metabolite: BF500-6	0	0	0	-[1]	20 Oct.
Medallion TL, 8 Nov.	Fludi-oxonil	36	Fludioxonil	0.91	2.96	78.8	0.050	17 Nov.
			Metabolite: CGA 192155	0085	0.27	14.8	100	17 Nov.

Although the maximal concentrations of prothioconazole-desthio, trifloxystrobin and boscalid in drainage water were 5-10 higher than the previous year, the ERL value was - as in 2016-2017 - exceeded only for prothioconazole-destio and fludioxonil (Table 5a). When averaged over the entire winter season, the concentration in drainage water was lower than the ERL for all fungicides and metabolites.

Except for the pyraclostrobin metabolite BF500-6, the maximum concentration of fungicides and metabolites in surface runoff were higher in 2017-18 (Table 5b) than in 2016-17. The ERL was exceeded by several orders of magnitude for trifloxystrobin and fludioxonil, approximately 50 times for prothioconazole-desthio and pyraclostrobin, and 17 times for boscalid. The highest concentrations of prothioconazole, trifloxystrobin, boscalid, pyraclostrobin and their metabolites were found on 20 Oct. after application of Delaro SC 325 and Signum on 18 Oct., while the highest concentration of fludixonil was found on 17 Nov. after application of Medallion on 8 Nov. In the first case, the high concentration may be explained by 38 mm rainfall starting 30 hours after fungicide application on 18 Oct. In the second case there was no frost in the soil at the application of Medallion on 8 Nov., but a cold period followed four days later, thus resulting in frozen greens and no infiltration at the subsequent moderate rainfall (9 mm before sampling).

As would be expected from the high concentrations, Table 5 shows that the total loss to the environment of most fungicides during the winter 2017-2018 was more severe in surface runoff than in drainage water. Exceptions to this were prothioconazole, the fludioxonol metabolite CGA 192155, and - most notably - the trifloxystobin metabolite trifloxystobin acid for which the highest losses were found in water that had passed through the rootzone.

There was no effect of organic amendment to the rootzone or establishment method on fungicide losses in surface runoff. In contrast, the leakage of trifloxystrobin acid and the fludioxonil metabolite CGA 192 155 were significantly lower from sodded than from seeded greens (Table 6). A similar trend ($P<0.10$) was seen also for fludioxonil (Table 6) and can be explained partly by less drainage (Table 3), but mostly because this and other fungicides will sorb to thatch organic matter.

For CGA 192155 there was also a significant effect of organic amendment with three times higher losses from the compost-amended than form the peat-amended rootzone (data not shown). This may have been due to a faster microbial degradation of fludioxonil, as the compost-amended rootzones had a pH more optimal for microbial activity than the peat-amended rootzones.

Table 6. Main effect of seeding vs sodding on accumulated leaching of some fungicides and their metabolites, 18 Oct. 2017 – 6 Apr. 2018.

	Prothio-conazole, µg/m2	Metabilite: Prothio-conazole-desthio, µg/m2	Tri-floxy-strobin µg/m2	Metabolite: Trifloxy-strobin-acid, µg/m2	Bos-calid, µg/m2	Pyraclo-strobin µg/m2	Fludi-oxonil - µg/m2	Fludioxonil metabolite CGA 192155 µg/m2
Seeding	5.0	11.2	0.36	6389	6.4	0.41	2.13	521
Sodding	4.9	10.9	0.35	5303	5.3	0.32	1.18	385
P-value	NS	NS	NS	**	NS	NS	(*)	*

4 Conclusions and recommendations

In line with former STERF projects (Aamlid 2014), the results showed an overall low risk for fungicide contamination of ground og surface water from water draining through the USGA-spec. rootzones. This is espcially the case once the greens have reached a certain age and developed a thatch layer. Inclusion of at least 1 % (w/w) organic matter in the rootzone, as practiced by most greenkeepers / contractors, further reduces the risk for fungicide leaching (Aamlid 2014).

The maximum concentrations of fungicides and their metabolites in surface runoff were, on the other hand, very high, and we are concerned about the high levels detected of prothioconazole-desthio, pyraclostrobin and fludioxonil that fall in the category of high chronic toxicity to aquatic organisms at one or several trophic levels. A relevant question is if this is a typical situation on golf courses. Especially the data from 2017-2018 seem to represent a worst-case scenario with a high rainfall episode 24 h after spraying Delaro and Signum, and green freeze-up and thus limited infiltration followed by high precipitation and recurring freezing and melting episodes after spraying Medallion. It must also be remembered that the plots at Landvik had a high surface inclination (5%) and that the collectors for surface water were placed at the end of each plot without a 3 m wide buffer strip to open water as prescribed by the Norwegian Directive on Pesticide Use. Some fungicides even have a wider buffer zone required on their label, e.g. 5 m on the Swedish label for Medallion and 10 m on the Norwegian label for Delaro. While the effect of buffer strips will be reduced if the soil freezes up shortly after application, our findings emphasize the importance of strict compliance with these zones to avoid fungicide contamination of open water.

There are also other precautions that may be taken by the greenkeepers to avoid surface runoff:

- The green must be maintained and the thatch controlled so that a severe reduction in infiltration capacity is avoided as the green gets older. Most greens on golf courses have lower infiltration rates than the new sand-based greens used in this experiment. Deep aeration may be one measure that can help to avoid surface runoff at least until the soil freezes before winter.
- As documented after applying Delaro and Signum on 18 Oct. 2017, the rainfastness of most fungicides stated on the label (usually 1-2 hours) is no guarantee that the products are absorbed and will no longer contaminate surface water. American studies conducted during the growing season showed significant reductions in runoff if the time from fungicide application until the first rainfall increased from 12 to 24 h (Branham et al. 2005). When applying fungicides at low temperatures in the late fall, this safety period should probably be even longer. For the greenkeeper, it is therefore important to observe the long-term weather forecasts and ensure there is no risk for high rainfall episodes during the first week after application. Turfgrass fungicide sorption and the risk for surface runoff at various temperatures and rainfall timings/intensities in the autumn could perhaps be a topic for further research under controlled conditions.
- It is well recognized that fungicide applications <u>on frozen greens</u> do not have the anticipated effect of turfgrass diseases and - on top of that – pose a threat to the environment. Perhaps less documented is the increased risk for contaminatin of surface water if the green freezes within a few days after fungicide application. As the winter climate tends to become more unstable with frequent freezing and melting episodes and higher rainfall intensities, there may perhaps be a reason to discuss the timing of the last fungicide application before winter. With the old contact fungicides such as iprodion, it was recommended to postpone the application as close to anticipated soil-freeze up / snowfall as possible. Today the typical contact fungicides have been replaced by new chemistries (on the Scandinavian market primarily Medallion), that are better absobed by the leaves and not as dependent on late application. Earlier timing of the last fungicide

application befor the winter is likely to reduce the risk for surface runoff due to rain falling on frozen greens.

- Finally, greenkeepers and golf course architects are encouraged to discuss to what extent it is feasible to constuct basins or collection areas where surface water from greens can accumulate before infiltration. A relevant question is if green bunkers may play a role in this regard.

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