



Leaching of fungicides from golf greens: quantification and risk assessment

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Summary

Fungicides are used in autumn on golf greens in Scandinavia to control snow mould, which can significantly damage the overwintering ability of the grass, and thus impair playing quality. Environmental concerns, especially with respect to the risks of leaching to receiving water bodies (i.e. groundwater and surface water), have led to increasing pressure against the use of pesticides on golf courses in recent years. This pressure is being heightened by reports of findings of pesticide residues in drainage water from golf courses. In this project, our objectives were to i.) assess the leaching risk associated with fungicide use on golf greens in Scandinavia, ii.) gain a better understanding of the processes controlling fungicide leaching from golf greens, and iii.) identify, recommend and encourage the adoption of green construction and management practices that minimize leaching to receiving water bodies. We monitored the leaching of the fungicide Iprodione from the research green at Fullerö, Västerås, and measured degradation and sorption properties of Iprodione in laboratory batch and incubation experiments on root zone material taken from Fullerö. We used this data to calibrate and validate the pesticide leaching model MACRO. The calibrated model was then used as a basis for a leaching risk assessment. We also ran ‘scenario’ simulations with the model to demonstrate the effects of root zone organic matter content on the leaching risk.

The main findings and recommendations were as follows:

- Degradation of iprodione was initially very rapid (half life < 1 day), which was attributed to microbial adaptation due to repeated applications of the compound. After this initial metabolic degradation phase lasting c. 5 days, degradation proceeded at a slower rate (half-lives 22 to 38 days).
- Iprodione was moderately strongly adsorbed to the green soil. The isotherm was approximately linear with a K_{oc} value of $400 \text{ cm}^3 \text{ g}^{-1}$.
- Despite the rapid breakdown, concentrations in drainage water from the Fullerö green exceeding the surface water quality guideline value ($0.2 \mu\text{g L}^{-1}$) were occasionally found.
- The model matched the hydrological observations reasonably well, but could not match the peak concentrations of iprodione found in drainage water. This was attributed to rapid preferential finger flow in the green, due to water repellency.
- The scenario simulations showed the great potential for minimizing losses of fungicides by appropriate green construction practices. Increasing the organic matter content in the root zone from 2 to 3% virtually eliminated leaching, while decreasing it to 1% increased leaching by a factor 20.
- Although fungicides can leach from USGA type greens in environmentally significant concentrations, their construction does offer some advantages. They are designed to optimize air-water relations in the root zone which should minimize fungal attack and reduce the need for fungicides. Regular use of surfactants should reduce leaching risks by eliminating water repellency.

A detailed description of the work performed and the conclusions and recommendations reached can be found in the two appendices. Appendix 1 is a popular science article written in Swedish that will shortly be submitted to ‘Greenbladet’. Appendix 2 is a scientific paper that has been submitted to the international journal ‘Pest Management Science’.

Appendix 1: Artikel som ska skickas till 'Greenbladet'.

Fungicidbesprutning på golfbanor: hur stora är riskerna för omgivande vattendrag och dammar?

De senaste årens ökade fokusering på ekologiska risker med användning av bekämpningsmedels i samhället har bidragit till en intensifierad debatt om rådande skötselrutinerna på golfbanor. Detta gäller framförallt fungiciderna som sprids på hösten/tidig vinter för att säkerställa en hög spelkvalitet på våra golfbanor genom att motverka snömögeln framfart. Nya och hårdare restriktioner för spridningstillstånd för golfbanor som ligger inom vattentäktområden förväntas också som följd av EU:s nya ramdirektivet för vatten. Under 2004 avslutades ett projekt vid Sveriges Lantbruksuniversitet (SLU) med målet att studera utlakningen av fungicider från svenska golfgreener, samt att uppskatta eventuella miljörisker. Projektet finansierades av Stiftelsen för Forskning om Grönytor för Golf (SFG), en organisation som aktivt stöder forskning kring frågor viktiga för golfens framtid i Skandinavien. I projektet har vi tittat på utlakningen av iprodion som är det verksamma ämnet i Rovral/Chipco green. Under hösten och vintern 2003 pågick provtagningen av dräneringsvattnet från SGFs försöksgreen av USGA-typ på Fullerö GK utanför Västerås. Greensanden analyserades också för att studera spridningen i greenprofilen efter iprodion-applisering.

Vad styr utlakning ?

Utlakning innebär att ett ämne efter spridning transporteras nedåt och ut ur en jordprofil. Det kan innebära att ämnet når ner och förorenar grundvattnet eller leds bort med dräneringsvattnet om den underliggande jorden är ogenomsläpplig (dvs en tät lera). I det senare fallet kan ytvatten som bäckar och sjöar drabbas. De skadliga miljöeffekter som kan uppstå beror på mängden som läcker ut, ämnets giftighet samt ekosystemets känslighet.

Risken för att ett ämne ska lakas ut bestäms av dess kemiska och fysiska egenskaper, jordens egenskaper samt andra inverkan faktorer som klimat och skötselrutiner. Ett enskilt ämnes utlakningspotential bestäms till stor del av dess förmåga att binda till jordpartiklar samt dess stabilitet mot kemisk och biologisk nedbrytning, två egenskaper som kan variera kraftigt mellan olika bekämpningsmedel.

De verksamma ämnena i flertalet av de bekämpningsmedel som finns på marknaden är uppbyggda av långa atomkedjor. Dessa ämnen attraheras av och adsorberas (binder) till mull. Mull består av långa kolkjedjemolekyler som bildats under nedbrytningen av organiskt material i jorden. En jord med hög mullhalt kan därför anses vara bättre ur ett utlakningsperspektiv än en jord med lägre mullhalt. De aktiva ämnena i ett bekämpningsmedel reagerar med sin omgivning. Molekyler kan då sönderdelas och bilda restprodukter, s.k. metaboliter. Metaboliternas egenskaper skiljer sig ofta från modersubstansen i fråga om t.ex. giftighet och rörlighet i mark. Det är biologiska och kemiska processer i mark och vatten som ser till att denna sönderdelning sker. Mikrobiell nedbrytning sker när bakterier använder bekämpningsmedlet som näringskälla. Omvandling av ämnen kan också ske genom kemiska processer som fotolys och hydrolys. Ett ämnes halveringstid är ett mått på nedbrytninghastigheten. Halveringstiden är tiden det tar innan halten av ett ämne i jorden har reducerats till hälften av den ursprungliga mängden. Ju kortare halveringstid, desto större är chansen att ämnet har hunnit brutits ner innan skadliga halter lakas ut från jordprofilen i dräneringsvattnet.

Förlusterna är låga dock ibland signifikanta för vattenlevandeorganismer

En simuleringsmodell (MACRO) användes i projektet för att tolka försöksresultaterna och för att kunna studera de processer som styr utlakning från en golfgreen. MACRO som utvecklats på SLU, har använts i flera EU-länder för riskbedömning av bekämpningsmedelsanvändning. Programmet gör det möjligt att simulera hur vatten flödar och hur bekämpningsmedel transporters och omvandlas i jorden.

Eftersom nedbrytningshastigheten och bindningsförmågan är de två viktigaste parametrarna som påverkar utlakningen var det viktigt att noggrant bestämma dessa. Detta gjordes i två experiment i laboriemiljö. I det första experimentet behandlades jordprov från de översta tre cm av greensanden och jord från djupare ner i profilen med iprodion. Jordproven ställdes sedan i mörker och en konstant temperatur på 20°C. Med jämna mellanrum analyserades jordproven för att se hur mängden av ämnet minskade med tiden. Resultatet visade på en mycket snabb nedbrytning av iprodion under experimentets första dygn, troligen pga att vissa populationer av bakterie växte genom att utnyttja det tillförda ämnet som energikälla. Halveringstiden beräknades till ca 17 timmar, vilket kan anses vara extremt snabbt. Den initiala snabba nedbrytning följdes av långsammare nedbrytning med en halveringstid på 22-39 dygn. I det andra experimentet analyserades hur väl ämnet binder till greensanden. Detta fastställdes genom ett så kallat skakförsök, där jord och lösningar med olika koncentrationer av iprodion skakas för att avgöra förhållandet mellan mängden av ämnet i vätskan och mängden bundet till jorden. Iprodion visade sig adsorberas relativt starkt till greensanden.

Resultatet från laborieförsöken användes tillsammans med väderdata för att simulera samma tidsperiod då mätningarna genomfördes. Modellen simulerade att merparten av det som återstod av ämnet återfanns i den övre delen av profilen (pga den starka adsorptionen), vilket också bekräftades av jordproverna som visade på att huvuddelen av den tillförda mängden iprodion fanns kvar i de översta 10 cm av jordprofilen. Iprodion återfanns i dräneringsvattnet, men koncentrationerna var generellt låga, strax över den gräns vid vilken iprodionhalten kan bestämmas (= 0.01 mikrogram/liter, 1 mikrogram = miljondels gram). Vid ett tillfälle uppmättes dock en koncentration på 2 mikrogram/liter, bara några veckor efter spridningen. En sådan snabb utlakning kunde inte beskrivas av modellen, och kan endast förklaras genom någon form av 'förbi- eller kortslutningsflöde' (på eng. 'Bypass', 'Short-circuit' eller 'Preferential flow') dvs att merparten av regnvattnet rinner igenom en liten andel av växtbädden medan resterande andelen förblir torr. Våra tester genomförda på växtbäddsmaterialet visar att detta troligen beror på att greenen är i viss mån vattenavstötande.

Tidigare miljöövervakningsstudier har också visat på utlakningsförluster och koncentrationer av iprodione i samma storleksordning. Dessa värden överstiger ibland riktvärdet för Iprodion (= 0.2 mikrogram/liter). Dessa riktvärden har nyligen tagits fram av KemikalieInspektionen med syfte att skydda känsliga arter i vattensystem som sjöar och vattendrag. Dock måste hänsyn tas till den utspäddningseffekt som uppstår på grund av att golfgreenerna endast utgör en liten del av en golfbana eller ett tillrinningsområden till t.ex. en bäck. Detta innebär att den slutgiltiga koncentrationen i ett akvatiskt ekosystem blir betydligt lägre än de koncentrationer som uppmätts i dräneringsvattnet.

För att studera hur olika green egenskaper påverkar utlakningen så utfördes några "scenariosimuleringar" med modellen. I det här fallet undersöktes hur greenens mullhalt skulle kunna påverka utlakningen. Den simulerade utlakningen ökade 20 ggr. när mullhalten sänktes från

2% till 1%, men minskade till odetekterbara nivåer vid en mullhalt på 3%. Enstaka provtagningar från försöksparcellerna med olika mullhalter på Fullerögreenen visar på en effekt av mullhalten av samma storleksordning.

Praktiska implikationer och slutsatser

Den snabba nedbrytningen av iprodion i golfgreensanden tyder på att vissa grupper av mikroorganismer har anpassat sig till att använda ämnet som näringskälla. Detta är en effekt av upprepade behandlingar med ämnet. Det har kommit många rapporter om att Chipco Greens effekt har minskat, vilket oftast har förklarats med uppbyggnad av resistans hos snömögel. Att det sker en allt för snabb nedbrytning av ämnet efter applicering kan vara en annan möjlig förklaring. Men det bör tilläggas att i praktiken hamnar iprodion på bladytan direkt efter appliceringen och här är det oklart om samma snabba nedbrytningensförlopp sker.

Vi har tittat på utlakning som en viktig förlustväg, men det är inte den enda transportvägen för fungicider att nå vattendrag. En annan möjlig väg för ämnet att nå ytvattnet kan vara genom ytavrinning. Under sommarhalvåret är denna transportväg av liten betydelse eftersom greenens vattengenomsläpplighet ska vara tillräckligt hög för att ta emot allt regn. Ytavrinning kan dock förekomma i samband med snösmältning eller nederbörd när marken är frusen. Våra beräkningar visar att koncentrationer av iprodion i ytavrinning under vinterhalvåret skulle kunna vara betydelsefulla, men inga mätningar har hittills genomförts.

Våra resultat tyder på att miljöriskerna förknippat med applicering av iprodion på golfgreenar av USGA-typ är inte försumbara och att det finns anledning till ett stort mått av försiktighet, särskilt med tanke på hur viktig mullhalten tycks vara. Den ideala mullhalten i en golfgreen diskuteras ofta. Att konstruera greener med ytterst låg mullhalt har nyligen förespråkats som ett alternativ. Den här studien visar på hur känsligt ett sådant system skulle vara. Fungicidanvändning på en sådan green kan ej rekommenderas förrän mullhalten har hunnit bli tillräckligt hög, vilket sker först efter många år. Även om en viss förlust av fungicider förekommer, har USGA greener troligen stora miljöfördelar jämfört med alternativen (t.ex. gamla matsjordsgreener). Snömögeln trivs bäst under fuktiga förhållanden och USGA greenen är designad för att optimera vattenförhållanden i växtbädden: överskottsvattnet dräneras effektivt bort så att växtbädden luftas ordentligt. En förnuftig skötselplan för en USGA green, där mekanisk luftning ingår bör minska riskerna för snömögelangrepp och resulterar i en betydelsefull minimering av fungicidanvändning enligt IPM (Integrated Pest Management) principer dvs att ingen profylaxisk besprutning förekommer. Vidare bör regelbunden användning av vätemedel minska utlakningsrisken vid eventuella fungicidappliceringar.

Appendix 2: Artikel inskickad till 'Pest Management Science'

Sorption, degradation and leaching of the fungicide Iprodione in a golf green under Scandinavian conditions: measurements, modelling and risk assessment

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1 **Abstract:** In cold climates, fungicides are used on golf greens to prevent snow
2 mould causing serious damage to the turf. However, fungicide residues have
3 been detected in runoff from golf courses, which may lead to restrictions on use.
4 There is therefore an urgent need to improve understanding of the processes
5 affecting leaching of fungicides from turfgrass systems to allow identification of
6 green construction and management practices that minimize environmental
7 impacts. In this study, we monitored the leaching of the fungicide iprodione in a
8 putting green. Sorption and degradation of iprodione was measured in batch
9 and incubation experiments and the simulation model MACRO was used as a
10 risk assessment tool. Degradation of iprodione was bi-phasic, with a rapid initial
11 phase (half-life 17h) caused by enhanced biodegradation. Degradation rates
12 slowed considerably after 5 days, with half-lives of up to 38 days. Sorption of
13 iprodione was linear, with a K_{oc} value of c. $400 \text{ cm}^3 \text{ g}^{-1}$. MACRO reasonably
14 accurately matched measured drainflows and concentrations of iprodione in soil
15 and drainflow. However, peak concentrations in drainage were underestimated,
16 which was attributed to preferential finger flow due to water repellency. The
17 results also showed the importance of the organic matter content in the green
18 root zone in reducing leaching. It was concluded that with ‘reasonable worst-
19 case’ use, losses of iprodione from greens can occur at concentrations exceeding
20 water quality limits for aquatic ecosystems. Snow mould problems should be
21 tackled by adopting green root zone mixes that minimize leaching and ‘best
22 management practices’ that would avoid the need for intensive prophylactic use
23 of fungicides.

24 **Keywords:** Iprodione, golf green, degradation, adsorption, leaching, modelling

1 **1 INTRODUCTION**

2 The popularity of golf in Sweden is steadily increasing, putting more pressure on golf
3 course superintendents to prolong the season and to maintain and improve turfgrass
4 quality. Due to the long cold Scandinavian winters, turfgrass is susceptible to fungal
5 diseases like pink and grey snow mould (*Microdochium nivale* and *Typhula*
6 *incarnata*). Fungicides are widely used in late summer and autumn to prevent these
7 diseases causing serious damage to the overwintering turfgrass. However, increased
8 public and political awareness over environmental issues, along with reports of
9 pesticide detections in runoff water from golf courses, has led to a debate over current
10 turfgrass management practices. Moreover, new legislation introduced under the EU
11 Water Framework Directive will most likely lead to more restrictions on pesticide use
12 on golf courses in certain areas, for example in groundwater abstraction districts. This
13 implies a need to quantify the possible adverse environmental effects of pesticide use
14 on golf courses and to improve our current understanding of the processes and factors
15 affecting leaching of pesticides from turfgrass systems. This would allow
16 identification of ‘best management practices’ that would help to minimize
17 environmental impacts.

18

19 Golf greens are today almost exclusively constructed according to recommendations
20 developed by the US Golf Association. The guidelines stipulate a coarse gravel
21 drainage layer overlain by a 30 cm sandy thick root zone material.¹ The practical
22 benefit of this construction is the establishment of a capillary ‘barrier’ between the
23 two layers, which ensures an adequate retention of plant available water in the root
24 zone and effective drainage of excess water to the underlying drainage system

1 embedded in the gravel. However, this green construction may represent a high-risk
2 environment for pesticide leaching. This is partly because the soil is shallow, which
3 limits the possibilities for attenuation of leaching by adsorption and degradation, but
4 also because a combination of regular irrigation and low transpiration (due to the
5 restricted rooting depth and low mowing height) results in high percolation rates.
6 Furthermore, the organic matter contents at the lower end of the range recommended
7 for USGA golf green sand beds (1%-2%)¹ are relatively small compared with many
8 agricultural topsoils. Wu et al.² studied the leaching of two fungicides, metalaxyl and
9 chlorothalonil, used on golf greens. The results showed the importance of strong
10 adsorption, since metalaxyl started to leach two months after application, whereas the
11 more strongly-bound compound chlorothalonil remained in the upper part of the
12 profile during the study (120 days). Petrovic et al.³ also showed that metalaxyl was
13 prone to leach from golf greens. In contrast, the leaching of two insecticides,
14 chlorpyrifos and trichlorfon, below 10 cm depth in a USGA-type golf green was
15 found to be negligible during two experiments that lasted 72 days.⁴

16

17 On the other hand, some features of the golf green environment may favour
18 adsorption and degradation of pesticides, and reduce leaching risks. For example, it is
19 often argued that 'thatch', an organic mat made up of more or less decomposed root
20 and stem material located between the growing turfgrass and the soil surface,⁵
21 reduces leaching. Organic matter in thatch is less humified compared to soil organic
22 matter, which is reflected in somewhat smaller K_{oc} values. However, adsorption is
23 still stronger in thatch due to the larger organic matter content.⁶ Thatch has also been
24 found to contain 40 to 1600 times more bacteria than the underlying soil⁷ which

1 favours faster biodegradation⁸ and reduces leaching.⁹ However, modern golf course
2 management practices aim to prevent thatch build-up on greens, since it leads to a
3 deterioration of physical properties, inducing wetter conditions that encourage fungal
4 growth and increase the need for fungicide use.^{10,11}

5
6 In this study, we focus on the leaching of the fungicide iprodione ([[(3,5-
7 dichlorophenyl)N-isopropyl-2,4-dioxoimidazolidine-1-carboximide]) one of only
8 three fungicides currently approved for use on golf greens in Sweden. Iprodione has
9 been detected in water draining from golf greens in Sweden and Norway.^{12,13}
10 However, these measurements were only made sporadically, and do not provide an
11 adequate basis for a proper risk assessment. The objective of our study was therefore
12 to monitor hydrological processes and the leaching of iprodione from an experimental
13 putting green constructed according to USGA guidelines and to use these
14 measurements as a basis for a risk assessment. A physically-based model of soil water
15 flow and pesticide leaching (MACRO¹⁴) was calibrated and validated against the
16 data. Parameter values for sorption and degradation of iprodione were based on the
17 results of batch and incubation experiments carried out on the green soil. Long-term
18 scenario simulations were run to assess i.) the risks for an aquatic ecosystem impacted
19 by iprodione leaching under Scandinavian conditions, and ii.) the likely effects of
20 different organic matter contents in the root zone on iprodione leaching. These latter
21 simulations serve as an illustration of how green construction practices may be
22 optimised to minimize the environmental impacts of pesticide use on golf courses.

23

1 2 MATERIALS AND METHODS

2

3 2.1 Model description

4 MACRO v.5.0 is a one-dimensional model of non-steady state water flow and solute
5 transport in soils.¹⁴ MACRO is a comprehensive model with many options, but only
6 those features activated in the current study are described below. For example,
7 MACRO deals with macropore flow, but this feature was not used in this study
8 because the sandy root zone material is structureless. Water flow is governed by
9 Richards' equation with hydraulic properties described by van Genuchten-Mualem
10 model¹⁵ and a sink term accounting for root water uptake.¹⁶ Potential
11 evapotranspiration is calculated using the Penman-Monteith equation. Solute
12 transport is modelled by the convection-dispersion equation, with adsorption
13 partitioning calculated using the Freundlich isotherm assuming instantaneous
14 equilibrium between solution and sorbed phases. Degradation follows first-order
15 kinetics with a rate coefficient corrected for soil temperature and soil moisture using a
16 modified Arrhenius equation¹⁷ and Walker's function¹⁸ respectively. Soil
17 temperatures are calculated by the heat conduction equation, with thermal properties
18 set internally in the model using pedotransfer functions based on soil texture, organic
19 matter content and bulk density¹⁹.

20

21 2.2 Site description

22 Fullerö Golf Club is located in Västerås, c.70 km west of Stockholm. A practice
23 putting and chipping green sown with creeping bentgrass (*Agrostis palustris* Huds.)
24 was constructed in 1999 according to USGA recommendations, with a 30 cm thick

1 root zone underlain by a drainage gravel layer containing pipes installed in a herring-
2 bone pattern. The green is divided into three separately drained plots each 250m² in
3 size, with root zone organic matter contents of approximately 2, 3 and 4 %. The sand
4 mix used for the root zone and the drainage gravel were analysed at the time of
5 construction of the green to determine particle size distribution by the pipette method.
6 Soil water retention for the root zone material was also measured using sand tables
7 and pressure plate apparatus. Van Genuchten's water retention equation was fitted to
8 the measured water retention data using the RETC program²⁰. The saturated hydraulic
9 conductivity of both the root zone material and the drainage gravel was determined
10 using a constant head permeameter. Table 1 shows the physical and hydraulic
11 properties of the root zone material and the drainage gravel. The particle size
12 distribution of the root zone material meets the USGA specifications reasonably well,
13 although the fraction of fines (clay, silt and very fine sand) is slightly larger than
14 recommended.¹ Table 2 shows that the functional characteristics of the root zone in
15 terms of permeability and water retention mostly meet USGA specifications, although
16 the water-filled porosity is slightly larger than recommended. On the other hand, for
17 the drainage gravel, USGA specifications stipulate that the fraction less than 2 mm in
18 size should not exceed 10% by weight.¹ The gravel material used for the Fullerö
19 green contained 59% by weight of particles less than 2mm in size (Table 1). Table 1
20 also shows that the gravel drainage layer had a much smaller saturated hydraulic
21 conductivity than the overlying sand bed (17 vs. 370 mm h⁻¹) which is probably partly
22 due to the infilling of larger pores by fines migrating from the overlying sand bed.
23

1 A visual inspection of the soil profile showed no thatch development. Instead, the
2 surface 3 cm of the green soil consisted of a mix of sand top-dressing and grass roots.
3 In the plot constructed with a nominal 2% organic matter content in the root zone,
4 measurements on a LECO CHN 932 analyzer gave organic carbon contents of 1.24,
5 1.45, 1.38 and 1.10% at 0-3, 3-10, 10-20 and 20-30cm depth respectively.

6

7 Golf greens are prone to water repellency, which can result in poor playing quality
8 due to uneven soil wetting and poor grass growth in 'dry spots'.²¹ Water repellency
9 can also have serious environmental consequences since it affects water flow and
10 solute transport patterns.²² A water drop penetration test²³ was therefore carried out to
11 examine the water repellency of the soil at 1, 3, 5 and 10 cm depth. Measurements
12 were made 3 hours, 5 hours and 1 day after sampling, in order to investigate the effect
13 of soil drying on water repellency. Table 3 shows that water repellency in the green
14 decreased with depth and increased with time after sampling (= dryness). Based on
15 this data, the upper few centimetres, consisting of a root mat mixed with top-dressing
16 material, can be classified as potentially water repellent.

17

18 Since its construction, the green has received iprodione applications once or twice
19 annually, with the exception of 2002 when no fungicides were applied. Iprodione was
20 applied on two occasions in 2001 (6.8 kg ha⁻¹ on 17th August and 3.1 kg ha⁻¹ on 19th
21 October) and 2003 (3 kg ha⁻¹ on both 2nd September and 14th November).

22

1 2.3 Field measurements

2 Volumetric soil water content and soil temperature in the green are recorded by a data
3 logger connected to CS615 Water Content Reflectometers (TDR) and 105T
4 temperature probes installed at 5, 15 and 25 cm depth. Drainage discharge from each
5 plot is measured continuously by tipping bucket. One sample of drainage water from
6 the 2% plot was taken in spring 2003 and analysed for iprodione to check that no
7 significant residues remained from the previous applications in 2001. This sample
8 showed only a trace concentration of iprodione ($<0.04 \mu\text{g L}^{-1}$). Grab samples of the
9 drainage water from the 2 % organic matter plots were then taken on six occasions
10 during an 86-day period between 17th September and 27th November 2003. Grab
11 samples of drainage water were also taken from the 3 % plot on two occasions
12 following the second iprodione application on 14th November.

13
14 Soil samples were taken with a coring device at 0-3, 3-10, 10-20 and 20-30 cm depth
15 on 10th December from the 2% plot, 26 days after the second application and a few
16 days prior to the onset of soil freezing. Six individual profiles were sampled, but
17 these were pooled into three replicate samples at each depth prior to analysis of
18 iprodione residues. For the extraction, 20 g of soil was mixed with 5 g of dessicant
19 (hydromatrix). Depending on the expected concentration, between 2 and 10 g was
20 extracted with a 50:50 mixture of dichloromethane and acetone. The extract was dried
21 with sodium sulphate and evaporated to exchange extractant (to cyclohexane/acetone
22 9:1) and adjust the final volume. Analysis of iprodione in the extract was performed
23 by gas chromatography with mass selective detector (GC-MSD).

24

1 2.4 Degradation of iprodione

2 A soil incubation study was carried out to determine the degradation rate and kinetics
3 of iprodione in the root zone material at Fullerö. The samples used in this experiment
4 were taken from the 2% organic matter plot in early December 2003 using a core soil
5 sampler and a stratified random sampling technique. Root zone material taken from
6 six locations at 0-3 and 10-20 cm depths was bulked and passed through a 2 mm
7 sieve before being used in the experiment.

8

9 Iprodione with a purity of 99% (Dr. Ehrenstorfer GmbH, Germany) was dissolved in
10 acetone. 100g of soil from each depth was treated with the iprodione solution. The
11 spiked soils were thoroughly mixed and left for a few hours to let the acetone
12 evaporate, before being mixed with 500g of untreated soil. The initial concentration
13 of iprodione (50 mg kg^{-1}) roughly corresponded to the maximum recommended dose
14 distributed evenly in a 1 cm thick layer of soil. For each soil depth, 10 plastic jars
15 with perforated lids were filled with 60 g of the treated soil. The samples were then
16 incubated in the dark at 20 °C. Deionised water was added on a weekly basis to
17 maintain the water content at approximately 60% of the maximum water holding
18 capacity. The incubation was discontinued for two replicate samples from each depth
19 at 0, 1, 4, 14 and 51 days after the beginning of the experiment. These samples were
20 stored at -20 °C until the end of the experiment when iprodione was analysed on
21 extracts from the soil samples. The procedures followed those described above.

22

1 2.5 Iprodione sorption

2 Sorption of iprodione in the root zone material was measured in batch sorption
3 experiments following OECD guideline 106 for the testing of chemicals. 35 ml of
4 0.01 M CaCl₂ was added to 6.15 g of soil from both 0-3 and 10-20 cm depths in 50
5 ml FEP centrifugation tubes. The suspensions were pre-agitated for 12 hours in an
6 end-over-end shaker. 5 ml of stock solution, comprising 0.01 M CaCl₂ and iprodione
7 was added to the tubes in order to obtain four initial concentrations ranging from 0.02
8 to 0.74 mg L⁻¹. This resulted in a liquid/soil ratio of approximately 6.5 L kg⁻¹. The
9 test tubes were agitated for 24 hours before being centrifuged at 3500 rpm for 1 hour.
10 The liquid phase was separated and analysed for iprodione content using GC-MS.
11 Shaking and centrifugation were conducted at a constant temperature of +8 °C to
12 approximate typical Scandinavian conditions in autumn. All samples were duplicated.
13 The experiment was conducted using one blank for each soil depth.

14

15 2.6 Model parameterisation

16

17 *2.6.1 Hydrological modelling*

18 The hydrological part of the model was parameterised from the data obtained from
19 measurements of the soil hydraulic characteristics. The root zone was divided into
20 two horizons, the top 3 cm containing top dressing material and the 30 cm thick root
21 zone containing the original sand mixture. Because of evidence of particle migration
22 from the sand layer, the 10 cm thick underlying gravel layer was also divided into two
23 separate layers: an upper part of low saturated hydraulic conductivity and a smaller
24 mean particle size, assumed to have been affected by the sand, and a lower part

1 unaffected by mixing with the sand with a saturated hydraulic conductivity
2 resembling that normally found in golf green drainage gravel (Table 4). A 2 cm thick
3 layer was used to represent the original soil underlying the golf green, assuming
4 typical van Genuchten parameters for clay (Table 4). A zero flow condition was
5 assumed at the bottom boundary, except when the soil was unsaturated, when
6 capillary rise into the profile was calculated assuming a zero pressure potential at the
7 base. Meteorological data recorded at Fullerö was used as driving data in the model,
8 together with recorded irrigation amounts and timings. Data for global radiation,
9 which was used to calculate potential evapotranspiration, had to be obtained from
10 Uppsala, 70 km north-east of Fullerö.

11

12 The parameters in van Genuchten's water retention equation were calibrated against
13 measured drainage and soil moisture content data from May to October 2003 using
14 SUFI, an inverse modelling tool²⁴ incorporated in the MACRO software package.
15 Root Mean Square Error (RMSE) was used as a measure of goodness-of-fit. A
16 comparison of Tables 1 and 4 shows that the saturated water content in the root zone
17 material was the only parameter markedly changed by this calibration procedure,
18 being reduced from 0.487 to 0.33 m³m⁻³. This may be evidence of incomplete wetting
19 during infiltration induced by water repellency.

20

21 *2.6.2 Pesticide fate modelling*

22 In a second step, the fate of iprodione was simulated using the experimentally
23 determined sorption and degradation parameters. Default parameter values in the
24 model for the effects of temperature and moisture content on degradation were

1 assumed. The simulation started on 1st May 2001 before the two applications in
2 autumn 2001 and finished on 10th December 2003, at the time of the soil profile
3 sampling. Each dose of iprodione was adjusted for volatilisation using an empirical
4 equation based on the vapour pressure of the chemical.²⁵ Using this method, 13 % of
5 the dose was calculated to be volatilised.

6

7 **2.6.3 Risk assessment**

8 Pesticide residues in aquatic ecosystems may have direct acute or chronic effects on
9 living organisms, but can also indirectly affect water-living organisms by secondary
10 effects. In a risk assessment, the exposure (i.e. concentration) of the pesticide in an
11 environmental compartment is compared to the ecotoxicological effects on key
12 indicator organisms. Long-term (19 year) simulations were carried out to evaluate the
13 exposure using historical meteorological data for the period 1976 to 1986. Iprodione
14 was applied each year on the same dates and with the same doses as in 2003. This
15 was considered as a ‘reasonable worst-case’ situation, although annual prophylactic
16 treatments should not be necessary in a properly functioning and correctly managed
17 USGA green. The same irrigation schedule was also used as in 2003. The last 15
18 years of the simulation were used in the analysis and a comparison was made between
19 simulated concentrations and legislative or guideline values. The Swedish Chemicals
20 Inspectorate (KemI) has recently developed water quality objectives for pesticides in
21 surface water²⁶. This value is set to 0.2 µg L⁻¹ for iprodione, while the Norwegian
22 guideline value is 2.5 µg L⁻¹.²⁷ The EU drinking water limit value is set to 0.1 µg L⁻¹
23 for any pesticide.

24

1 As the green area is a small fraction of the total golf course area, the dilution in
2 streams from clean run-off water from the golf course itself and from other parts of
3 the catchment can be considerable. This was accounted for in the risk assessment by
4 multiplying the leachate concentrations by a dilution factor. This factor (=17) was
5 estimated from a comparison of the iprodione concentrations measured in the
6 drainage water from a Norwegian golf green and in streamwater samples taken
7 immediately downstream of the golf course.¹²

8

9 ***2.6.4 Scenario simulations***

10 An accurately calibrated model can be used to evaluate likely effects of different
11 green construction and management practices on fungicide leaching. USGA
12 recommendations allow for a wide range of organic matter contents in the root zone
13 material (Table 2). The importance of the organic matter content in the sand bed for
14 iprodione leaching was investigated by simulating organic matter contents in the root
15 zone of 1, 2 and 3 %. The K_d values used in these simulations were calculated from
16 the K_{oc} value determined at 10-20 cm depth in the 2% plot. Both iprodione
17 degradation and the hydrology of the green were assumed to be unaffected by the
18 organic matter content in the root zone.

19

20

1 **3 RESULTS AND DISCUSSION**

2

3 3.1 Degradation of iprodione

4 The degradation of iprodione in samples from the two depths is shown in Figure 1a,b.

5 Degradation was not a first-order process. Instead, a rapid decrease of iprodione

6 amounts occurred in the first 5 days at a rate equivalent to a half-life of c. 17 hours at

7 both soil depths. The fast initial degradation was followed by a slower degradation

8 phase, with equivalent half-lives of 38.8 days and 22.4 days at 0 to 3 and 10 to 20 cm

9 depth respectively. The degradation rate coefficients for the two phases and the

10 ‘break-point’ between them were derived from least-squares fitting with the iterative

11 Levenberg-Marquardt algorithm. Such a bi-phasic degradation pattern is most likely

12 due to metabolic degradation induced by repeated applications of the compound,

13 leading to the growth of bacterial population strains that utilize iprodione as an

14 energy source. The dose added to the soil at the start of the incubation experiment

15 was the third occasion in six months that the green soil had been exposed to

16 iprodione. Walker et al. measured iprodione degradation rates in a sandy loam soil

17 exposed to 1, 2 and 3 treatments (with 50 days between each treatment).²⁸ The

18 apparent half-life decreased from 23 to 5 days in the soil treated twice. In the soil

19 treated three times, 90% of the iprodione was degraded after just two days. They also

20 found that a soil exposed to repeated low doses of iprodione showed a similar

21 degradation pattern as the soil from 10-20 cm depth in our experiment, with fast

22 degradation occurring after a short lag period of 1-4 days. Enhanced or accelerated

23 degradation of iprodione has also been demonstrated in several other studies.^{29,30,31}

24 Athiel et al. identified a bacterial strain degrading iprodione, using it as the sole

1 source of carbon,³² while Mercadier et al. isolated three more bacterial strains
2 responsible for the degradation of iprodione and its metabolites in adapted soils.³³

3

4 The MACRO model only accounts for first-order degradation kinetics. To account for
5 the observed bi-phasic pattern of iprodione degradation, the half-life in the surface 3
6 cm of the root zone was changed from 0.7 to 38.8 days, 5 days after each application.

7 A constant half-life of 22.4 days was assumed to be appropriate deeper than 3 cm,
8 mainly because of the practical difficulty in a modelling context of determining when
9 the microorganisms at this depth in the soil are first exposed to the compound.

10

11 3.2 Iprodione sorption

12 The batch sorption experiments showed linear relationships between equilibrium
13 concentrations in the liquid and solid phases. The sorption K_d values were 4.8 and 6.2
14 cm^3g^{-1} at 0-3 and 10-20 cm depth respectively ($R^2 = 0.97$ and 0.96). For non-ionic
15 compounds like iprodione, organic matter is usually the main soil constituent
16 controlling adsorption.³⁴ Calculated K_{oc} values were 385 and 447 cm^3g^{-1} , which are
17 similar to values reported in the literature.^{6,35} In the calculation of the K_d value at 0 to
18 3 cm depth, the total amount of iprodione in each test tube was reduced to account for
19 biodegradation, using the degradation rate observed in the incubation experiment and
20 accounting for the difference in temperature between the two experiments assuming a
21 Q_{10} value of 2.23.

22

23

1 3.3 Modelling

2

3 **3.3.1 Hydrological calibration**

4 A good fit between measured and simulated drainage flow was obtained (Figure 2).

5 The RMSE for the calibration period was 1.1 mm d^{-1} . The fit to measured water

6 contents was less good, with the model underestimating the dynamics of fluctuations

7 of water content in the green (Figure 3). A comparison of simulated and measured

8 values shows that the water content at 15 cm is better predicted (RMSE = 0.018 m^3

9 m^{-3}) than at 5 and 25 cm depth (RMSE = 0.033 and $0.051 \text{ m}^3 \text{ m}^{-3}$). It is not clear why

10 water contents are systematically overestimated at 25 cm depth.

11

12 **3.3.2 Soil temperatures**

13 Figure 4 shows that in the critical period following iprodione application in 2003,

14 simulated soil temperatures were generally larger than measured, with RMSE values

15 of 2.6 , 3.4 and $4.2 \text{ }^\circ\text{C}$ at 5, 15 and 25 cm depth respectively. The reason for this is not

16 known, but the treatment of heat flow in the model is rather simple: the model ignores

17 the energy balance at the soil surface, and assumes that the surface temperature can

18 be fixed equal to air temperature. This assumption may not be adequate for turfgrass.

19

20 **3.3.3 Pesticide fate**

21 Table 5 shows the measured concentrations in the drainage water from the plots with

22 2 and 3% organic matter content, and simulated values based on measurements of

23 adsorption and degradation in soil from the 2 % plot. The model was able to

24 accurately capture the small concentrations of iprodione ($\leq 0.2 \text{ } \mu\text{g L}^{-1}$) mostly found in

1 drainflow during the monitoring period. This leaching may have been due to
2 iprodione residues from applications in previous years. However, the much larger
3 concentration ($2 \mu\text{g L}^{-1}$) detected only two weeks after the second application of
4 iprodione on 14th November could not be matched by the simulation. One likely
5 reason for this may be uneven wettability due to water repellency, resulting in a
6 preferential ‘finger’ flow^{21,22,36}

7

8 Table 6 shows that the bulk of the iprodione residues were found in the top 10 cm of
9 the soil, with smaller concentrations found deeper in the profile. A large variation in
10 concentrations was found between replicate samples, especially in the surface layers.
11 Uneven wetting patterns due to water repellency (see above) is one likely explanation
12 for this, but variations in metabolic degradation rates due to pH variations may have
13 also been important.²⁹ Despite the difficulties that could have arisen due to the
14 occurrence of enhanced metabolic degradation, as well as errors in the simulation of
15 soil temperatures and water contents, the model matched the data reasonably well,
16 with simulated concentrations lying within the range of the measured data in the
17 surface two layers, and only slightly outside deeper than this. Thus, there is no
18 evidence to suggest that iprodione degradation was underestimated in the soil deeper
19 than 3 cm, even though the fast metabolic degradation phase found in the laboratory
20 experiment (Fig. 1b) was ignored in the modelling. Compared to the laboratory
21 experiment, the microorganisms were exposed to much smaller concentrations at this
22 depth in the green, and this may have failed to trigger metabolic degradation.

23

1 **3.3.4 Scenario simulations and risk assessment**

2 The results of the long-term simulations are shown in Table 7. For the baseline
3 simulation (2% OM), the peak leachate concentrations at no time exceeded $1.1 \mu\text{g L}^{-1}$
4 and the accumulated leached amount was less than 0.01 % of the total applied dose
5 during the 15 year period. Risk ratios express the relationship between the exposure,
6 expressed as a concentration in a water body, and ecotoxicological limit values or
7 drinking water guidelines. A risk exists if the risk ratio exceeds 1. Risk ratios for
8 iprodione leaching are shown in Table 8. Assuming a dilution factor of 17, simulated
9 concentrations exceed neither the Norwegian and Swedish limit values for surface
10 waters, nor the EU limit value for drinking water ($=0.1 \mu\text{g L}^{-1}$), which is relevant for
11 groundwater extraction and treated surface water. In the case of groundwater, the risk
12 of exceedance of $0.1 \mu\text{g L}^{-1}$ must be considered negligible, since the leachate from the
13 green must also pass through the original soil underlying the green, which has a
14 significant potential for adsorption and degradation. However, as indicated in Table 8,
15 even after accounting for dilution, the Swedish surface water quality objective has
16 been exceeded by occasional peak drainage concentrations observed in some previous
17 studies in Scandanavia.^{12,13} This confirms the impression gained from the test period
18 in 2003 (Table 5) that the model may tend to underestimate peak concentrations
19 leaching from golf greens, perhaps due to finger flow.

20
21 One additional exposure route is relevant for a risk assessment for use of iprodione on
22 golf greens under Scandinavian conditions: during winter, the green will be exposed
23 to intermittent snowfall and snowmelt, and soil freezing. Snowmelt or rainfall on
24 frozen soil may lead to surface runoff, especially later in the winter when the larger

1 soil pores, which are initially air-filled, become blocked with ice due to re-freezing of
2 infiltrating water.³⁷ Table 6 shows that despite the initial rapid degradation of
3 iprodione, c. 1.4 mg kg⁻¹ remained in the surface 3 cm of soil on 10th December 2003,
4 immediately prior to the first freezing event of the winter. Rough calculations suggest
5 that this would be equivalent to a concentration in soil water of c. 250 to 300 µg L⁻¹.
6 This implies that there is clear risk of winter surface runoff losses of iprodione
7 exceeding limit values, especially considering that degradation during winter is likely
8 to be quite slow due to the low soil temperatures.

9

10 The results of the scenario analyses shown in Table 7 show the great influence that
11 the organic matter content in the root zone is predicted to have on leaching. Total
12 losses are predicted to be 15 times smaller when the organic matter content increases
13 from 2 to 3%. This estimate is supported by a comparison of the measured
14 concentrations in drainage water from the 2 and 3% organic matter plots during the
15 major leaching event on 27th November, when the leachate concentration was 20
16 times smaller from the 3% plot (Table 5). Larger organic matter contents should also
17 reduce surface runoff losses, although here the effects are likely to be less dramatic,
18 since solution concentrations in the surface soil will be roughly proportional to K_d
19 values. The scenario analyses suggest that there is some scope to construct and
20 manage golf greens to minimize the environmental impacts of plant protection
21 products. It is also clear that serious problems can arise if insufficient attention is paid
22 to the environmental aspects of green construction and management. For example,
23 greens constructed from pure sand without mixing in organic matter have recently
24 been proposed as a cheap alternative to the standard USGA specification.

1 Furthermore, in the recent update to the USGA specification
2 (www.usga.org/turf/course_construction) inorganic amendments such as perlite and
3 zeolite are now accepted as a replacement for the traditional organic amendments.
4 Table 7 suggests that if either of these methods is followed, it is imperative that no
5 plant protection products are applied to the green, at least not for several years, to
6 allow sufficient time for root production and decay to build-up an adequate store of
7 humus in the root zone.

8

9 **4. CONCLUDING REMARKS**

10 An initial very fast degradation rate of iprodione (half-life c. 17 hours) was observed
11 in the laboratory, which was explained by enhanced biodegradation following
12 repeated high dose applications of the compound. Degradation rates slowed
13 considerably after 5 days, with half lives of c. 38 and 22 days found at 0-3 and 10-20
14 cm depth respectively. The effect of this bi-phasic degradation pattern on leaching
15 was difficult to quantify, since the effects of metabolic degradation can only be
16 indirectly and approximately mimicked in the model, as MACRO assumes first-order
17 kinetics. Sorption of iprodione in the green root zone material was to a good
18 approximation linear, with a K_{oc} value of c. $400 \text{ cm}^3 \text{ g}^{-1}$.

19

20 MACRO reasonably accurately matched measured drainflows, although simulations
21 of soil temperatures and water contents in the green were less accurate. Despite
22 moderately strong adsorption and rapid degradation, peak concentrations of iprodione
23 ($2 \mu\text{g L}^{-1}$) that exceeded water quality objectives for aquatic ecosystems were found
24 in drainage water within three weeks of application. These peak concentrations were

1 attributed to preferential finger flow in the green due to water repellency, and could
2 not be matched by the model. An overall good fit between predicted and observed
3 soil concentrations of iprodione in the green at Fullerö was found immediately prior
4 to soil freezing in early December. At this time, the highest soil concentrations were
5 found in the top 10 cm of the profile, with a mean value of 1.4 mg kg⁻¹ at 0-3 cm
6 depth, which suggests that there is also a risk of winter surface runoff losses of
7 iprodione exceeding limit values. However, no measurements were made that could
8 confirm the significance of this exposure route.

9

10 We conclude that with ‘reasonable worst-case’ use, losses of iprodione from golf
11 greens occur at concentrations that may exceed recently established water quality
12 limits for aquatic ecosystems. This has been confirmed by measurements made
13 elsewhere in Scandinavia.¹² Even though dilution from clean water may greatly
14 reduce the final concentration in the receiving water body, limit values may still
15 occasionally be exceeded. Such unacceptable leaching losses are prompting a search
16 for alternative solutions to the problem of snow mould on golf greens. These
17 alternatives might include the use of newer fungicides with more favourable
18 environmental fate characteristics (e.g. strobilurines). More fundamentally, adoption
19 of proper green construction and management practices that maintain well-aerated
20 conditions would reduce the frequency and severity of snow mould outbreaks,
21 thereby avoiding the need for intensive prophylactic use of fungicides. In particular,
22 this implies strict implementation of USGA specifications for green construction to
23 ensure proper water management. The selection of root zone and gravel drainage
24 materials, and the placement and design of drainage systems are especially critical in

1 this respect. Management practices that help minimize mould outbreaks include
2 regular aerification to avoid the build-up of thatch, and proper irrigation scheduling to
3 match plant water requirements and prevent over-watering. Regular use of surfactants
4 to ameliorate or prevent water repellency might also improve water use efficiency and
5 reduce leaching²¹. Finally, our scenario analyses suggest that it would be highly
6 beneficial if future revisions of the USGA specifications placed as much emphasis on
7 constructing greens to minimize environmental impacts (e.g. through selection of the
8 root zone organic matter content) as on optimizing grass health and playing quality.

9

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Figure Captions

1

2

3 Fig. 1. Iprodione degradation at a.) 0-3 cm and b.) 10-20 cm depth. Fitted lines
4 represent bi-phasic degradation kinetics with two first-order rate coefficients,
5 μ , in series (C/C_0 is the ratio between the measured concentration and initial
6 concentration of iprodione).

7

8 Fig. 2. Measured and simulated drainage rates a.), and accumulated drainage b.).

9

10 Fig. 3. Measured and simulated volumetric soil water contents.

11

12 Fig. 4. Measured and simulated soil temperatures.

Table 1. Physical and hydraulic properties measured in the green

Layer	Particle size distribution (μm)				Saturated hydraulic conductivity (mm h^{-1})	Residual water content (%)	Saturated water content (%)	van Genuchten's α (cm^{-1})	van Genuchten's N
	Clay (< 2)	Silt (2-60)	Sand (60-2000)	Gravel (>2000)					
Root zone	2.5	10.0	87.0	0.5	374	9.8	48.7	0.086	2.00
Drainage layer	1.6	2.5	55.1	40.8	17	1.4	41.1	0.23	1.84

Table 2. USGA recommendations for root zone materials.¹

Property	USGA recommendation	Fullerö green
Porosity	35-55%	49%
Air-filled porosity at 40 cm tension	15-30%	21%
Water-filled porosity at 40 cm tension	15-25%	28%
Saturated hydraulic conductivity	^a Normal 150-300 mm h ⁻¹ High 300-600 mm h ⁻¹	374 mm h ⁻¹
Organic matter content	^b 1-5% (ideal 2-4%)	2, 3 and 4% plots

^aThe 2004 update of the USGA specifications (<http://www.usga.org/turf>) only stipulates a minimum value of 150 mm h⁻¹

^bThe 2004 update of USGA specifications (<http://www.usga.org/turf>) makes no recommendations concerning organic matter contents in the root zone, only that the final root zone mix has the functional characteristics listed in the table above.

Table 3. Water drop penetration times (seconds)

<i>Depth</i> (<i>cm</i>)	Time after sampling			Classification	
	3 hr	5 hr	1 day		
1	4	9	482		
3	3	5	320	<5 sec	Wettable
5	<1	<1	7	5-600 sec	Slightly water repellent
10	<1	<1	<1	600-3600 sec	Severely water repellent

Table 4. Hydraulic parameter values used in the simulations

Layer	Saturated hydraulic conductivity (mm h ⁻¹)	Residual water content (%)	Saturated water content (%)	van Genuchten's α (cm ⁻¹)	Van Genuchten's N
Root zone	374 ^a	8.8 ^b	33 ^b	0.095 ^b	2.00 ^a
Drainage layer 1	34 ^b	1.4 ^a	41.1 ^a	0.15 ^b	1.50 ^b
Drainage layer 2	900 ^c	1.4 ^a	41.1 ^a	0.21 ^b	1.84 ^a
Clay	10 ^c	0 ^c	46 ^c	0.01 ^c	1.10 ^c

^aMeasured^bCalibrated^cAssumed

Table 5. Measured and simulated drainage concentrations ($\mu\text{g L}^{-1}$).

Date	Measured		Simulated
(2003)	2% OM	3% OM	
02-Sep	Application 1		
17-Sep	0.04	n.d.	0.027
19-Sep	0.05	n.d.	0.040
22-Sep	0.2	n.d.	0.044
29-Sep	Trace	n.d.	0.035
14-Nov	Application 2		
16-Nov	Trace	0.1	0.047
27-Nov	2.0	0.1	0.054

Trace = 0.01-0.04 $\mu\text{g/L}$.
n.d. = no data

Table 6. Measured and simulated iprodione concentrations (mg kg^{-1}) in the golf green profile (10th December 2003).

Depth (cm)	Measured				Simulated
	Mean	Min.	Max.	SE ^a	
0-3	1.4	0.2	3	0.83	2.86
3-10	0.71	0.05	2	0.64	0.17
10-20	0.006	0.004	0.009	0.0017	0.014
20-30	0.015	0.005	0.03	0.0076	0.0039

^a Standard Error of the Mean

Table 7. Simulated long-term leaching, with statistics on annual mean concentrations, maximum concentration and accumulated leaching of iprodione during 15 years (OM = organic matter content).

Simulation	Mean annual concentration		Maximum concentration	Accumulated loss to drains (% of dose)
	Median	80'th percentile		
	$\mu\text{g L}^{-1}$			
2% OM (Base simulation)	0.045	0.11	1.10	0.0092
1% OM	1.80	3.10	24.47	0.26
3% OM	0.0030	0.0071	0.072	0.00060

Table 8. Measured and simulated drainage water concentrations ($\mu\text{g L}^{-1}$), and corresponding risk ratios for various limit values.

	Highest concentration	With dilution	Risk ratios		
			EU Drinking Water	WQO ^a	MFI ^b
Simulated (Long-term)	1.1	0.06	0.63	0.32	0.02
Measured: Fullerö (2001) ^c	10	0.58	5.77	2.88	0.16
Measured: Vestfold (Norway) ^d	16	0.92	9.23	4.62	0.26

^a Water Quality Objectives developed by the Swedish Chemical Inspectorate (=0.2 $\mu\text{g/L}$).

^b Norwegian guideline value for aquatic ecosystems (=2.5 $\mu\text{g/L}$).

^c reference 13

^d reference 12

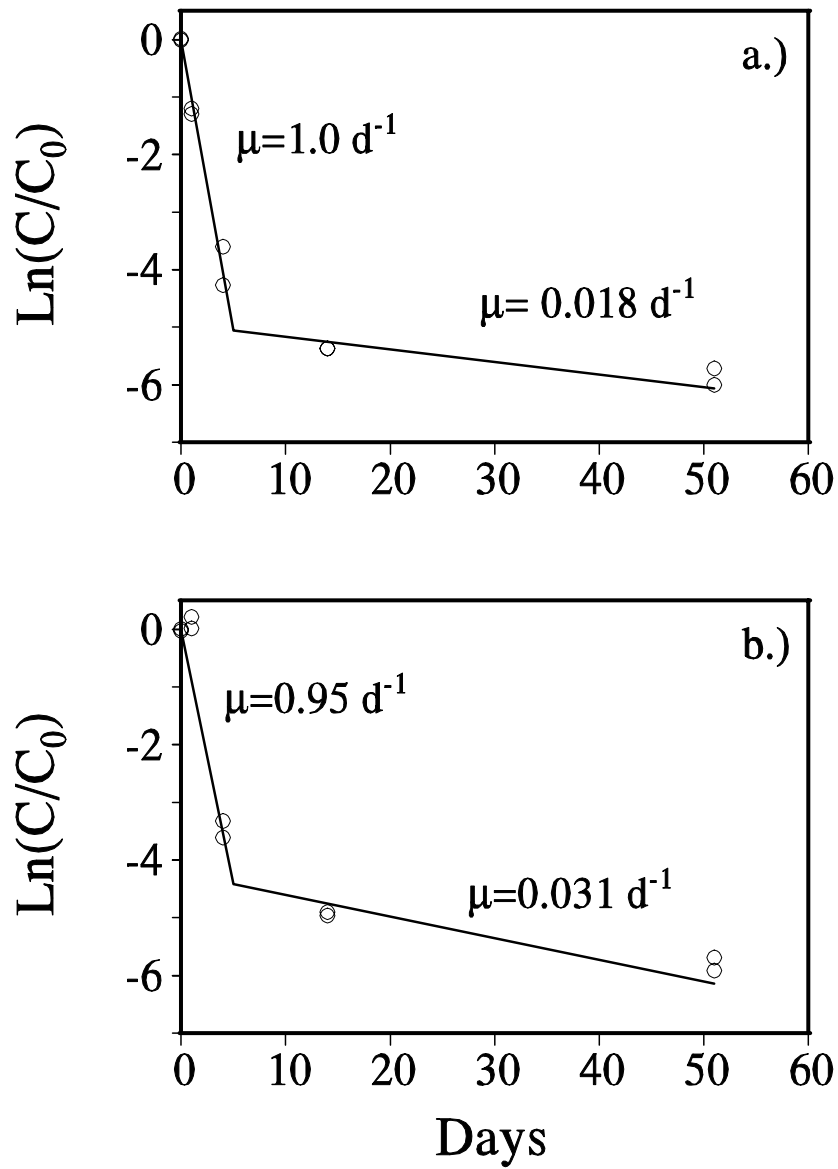


Fig.1

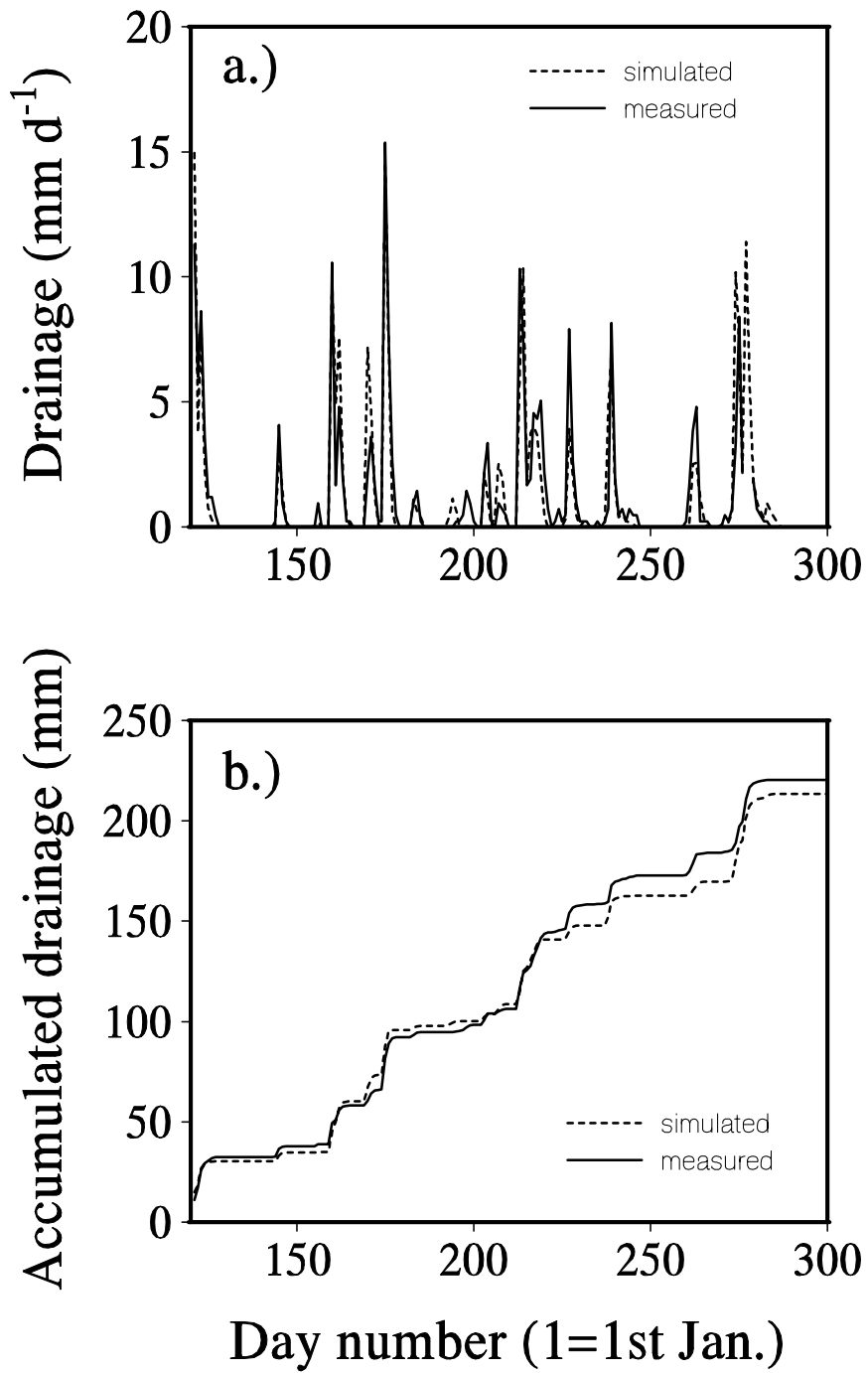


Fig. 2

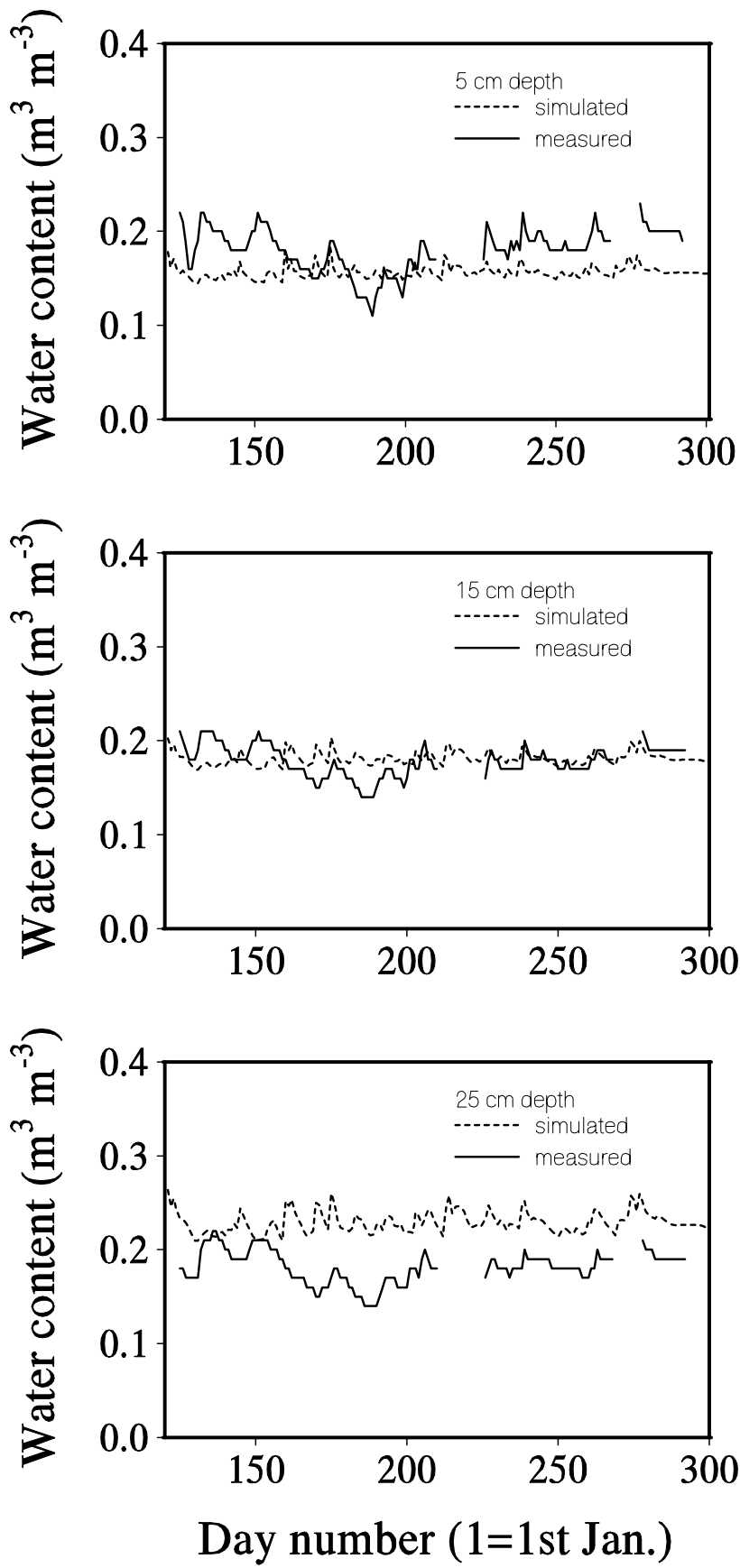


Fig. 3

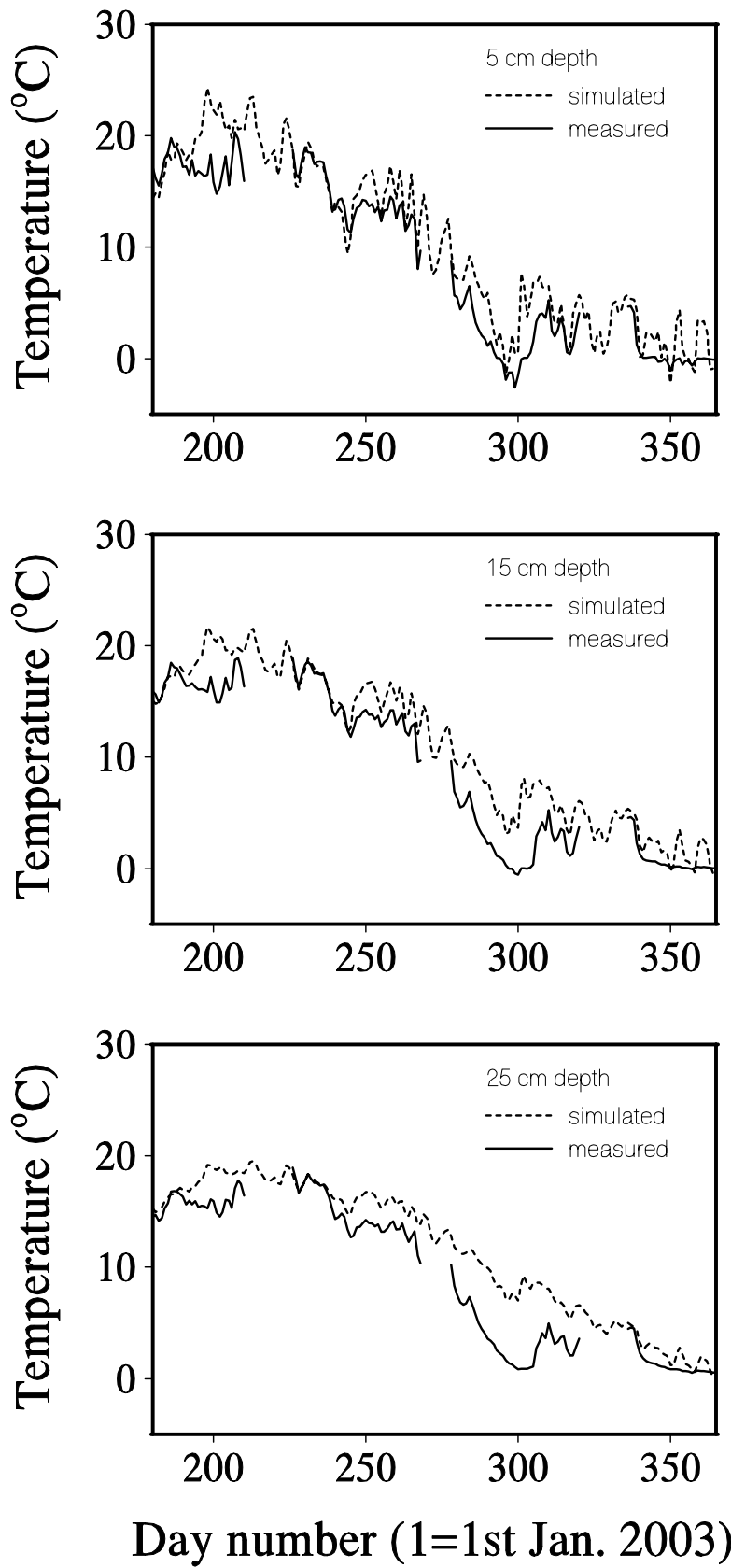


Fig. 4