Tools for environmental planning to reduce risks of leaching and runoff of pesticides to groundwater

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Abstract: Contribution of pollution from pesticides is often located to minor areas within a field. Areas with coarse textured materials in the soil profile often represent "hot spots" with high risk of leaching, but also areas with example structured clay soils may be "hot spots". Other areas can be slopes or bottoms in depressions on plateaus were water can be ponded in wet periods or in springtime before the frost has disappeared from the soil profile. If pesticides with high risk of leaching were avoided on these areas, the contribution to groundwater pollution could be reduced extensively. Up to now limited information or tools have been developed for farmers to identify these areas.

In a newly completed project, tools for groundwater and surface water protection was developed and evaluated. Three different types of tools have been developed: Topographical maps, risk tables and risk maps. Micro-topographical maps were developed to identify depressions and other vulnerable areas representing high risk of leaching and runoff. Tables of pesticide leaching risk to drainage and groundwater were derived from model simulations in spring cereals and potatoes with the mostly used plant protection strategies on the most common soil types for the areas. A meta-model was used for calculation of pesticide concentrations in groundwater and drainage water, coupled with digital soil maps and presented by Geographical Information Systems (GIS). Farmers from two areas evaluated the usefulness of these tools.

Generally the farmers' attitudes to the new tools were positive, but this type of information should be integrated in already existing planning tools at the farm, like fertilizer planning. The project produces large amounts of information and an electronic presentation readily understood and easy to follow is important. In some cases different soil types and topography within the farm represented different risk of leaching. In such cases, it is necessary to easily find pesticides to be used for all areas to avoid time consuming washing and change of equipment.

Keywords: Tools (Decision Support System), pesticides, leaching, groundwater, surface water, GIS

1. INTRODUCTION AND BACKGROUND

The Water Frame Directive and the Groundwater Directive have brought focus on the impacts of pesticides on groundwater into focus in Europe. In Norway the most important groundwater resources are located in alluvial deposits along the rivers. Such areas are used for intensive cereal and potato production, and groundwater investigations demonstrate that diffuse pesticide pollution from agriculture is a major threat to these aquifers (Eklo et al. 2002). Similarly, pesticides have also been found in groundwater in marine shore deposits in Norway (Pengerud et al. 2005). To reach the objective of reduced environmental impacts of pesticide use on groundwater in Norway, new tools for sustainable pesticide use have to be developed.

Recent research indicates that a major part of diffuse pesticide pollution originate from minor areas, "hot spots". A model study from Sweden showed that a small part (1%) of the catchment contributed to the main part (70 %) of the diffuse pollution at the farm. From other areas it has been reported that from 1 to 17 % of the area has contributed to 90 % of the pollution (Lindahl et al. 2005).

Both micro topographical conditions and soil properties will influence where these "hot spots" are situated. Areas with coarse materials in the soil profile often represent "hot spots" with high risk of leaching. Depressions in the terrain where water are collecting in wet periods or in snow melt periods before the frost has disappeared from the soil profile can be important "hot spots", also areas with structured clay soils can be vulnerable areas. In areas with cold winters below zero, large water quantities can be collected in terrain depressions during periods with frost in the soil, followed by rapid infiltration and transport of large water amounts down to groundwater in spring (Hayashi et al. 2003, Berthold et al. 2004, and Kværner et. al. 2005). Also the degradation of pesticide may vary with the topographical situation (Stenrød 2004) and the organic carbon content for example.

Several countries have made risk maps by linking pesticide models with digital soil maps within the geographical information systems (GIS). If pesticides with high risk of leaching were avoided on these areas, the contribution to groundwater pollution could be strongly reduced. Up to now limited information or tools for farmers have been available for identifying these areas. The objective of this study was to make suitable tools available for farmers which could be used in local environmental planning for reducing the risk of leaching and runoff of pesticides to groundwater and surface waters. Three different tools have been tested followed by evaluation from users in two selected areas.

2. MATERIAL AND METHODS

2.1. Overview of the project

The long term goal of the project was to contribute to national goals on environmental friendly and sustainable food production by developing tools for farmers to be used at farm level to reduce risk of leaching pesticides from agricultural soils. One sub-goal of the project was to develop three tools for farmers: (a) micro topographic maps to identify vulnerable areas at the two sites, (b) tables containing the risk of pesticide leaching and runoff from different soil types in the two areas (c) developing risk maps based on MACRO modeling and soil types. The other sub goal was to test and evaluate the usefulness of the tools and the attitude of the farmers to start using such tools.
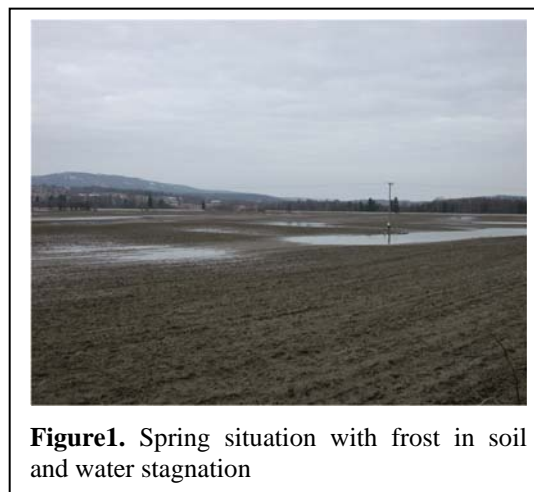

Figure1. Spring situation with frost in soil and water stagnation

Micro topographical maps should be developed to identify slopes and depressions representing high risk of leaching and runoff (Fig. 1). Tables containing the risk of pesticide leaching to surface and groundwater resources should be achieved from model simulation with MACRO_GV in the most common crops and soil types for possible selection of pesticides. Meta- model of MACRO coupled with digital soil maps should be developed and used for calculation of pesticide concentrations in groundwater and drainage water. Maps presented by Geographical Information Systems (GIS) would help farmers to be able to select the less harmful pesticide in the area. Two selected areas were used to test and evaluate the usefulness of the tools and to investigate the attitude among the farmers to use such tools.

2.2.   Selected areas

Two sites were selected for the project (Fig. 2). Each area is representing different cropping systems with different plant protection strategies and soils with different physical and chemical properties and thereby different vulnerability of pesticide leaching. Both sites represent areas with frequent use of pesticides.

The Grue site is located along the Glomma River in Hedmark County, north-east of Oslo along the river Glomma (Fig. 2). The area is situated above a deep basin filled with marine

Figure 2. The two selected locations, Grue and Heiabekken

deposits beneath a top layer of fluvial sediments. Clay can be observed below 13-15m depths. Above this level the deposits consists mainly of sand with a top layer of flood plain sediments of silt and sand. The area is dominated by permeable soils. Fluvic Cambisols cover 79 % of the area, while Arenosols cover 9 %. Areas with low permeability, consisting of Stagnosols, cover 6 %. These soils, however, can temporarily be completely saturated with surface water from heavy rainfall or snowmelt. Four other soil groups are represented, each covering only small areas. In several locations an iron pan was found at a depth of approximately 4 m. Such layers might increase local hydrological gradients and the velocity of transport of water and substances around washing sites. The thickness of the unsaturated zone varied between 1.8 and 5.9 m. The mean groundwater recharge is estimated to be 300 mm year^{-1}. The aquifer is characterised by groundwater flow towards the river Glomma in W, NW and N. Only during flood peaks in spring and autumn water will flow into the aquifer from the river Glomma. The hydraulic gradients and the velocity of the groundwater flow have been small (< 40 cm day $^{-1}$ at a hydraulic gradient of 0.2 %). The main crops in the area are potatoes and cereals. The region is important for the potato production at national scale.

The Heiabekken (Fig. 2) watershed is located in the south- eastern part of Norway in Østfold County on the eastern side of the Oslofjord. The stream Heiabekken is the only stream from the watershed and flows into Kurefjord, a small part of Oslofjord. Water samples collected downstream Heiabekken are monitored for pesticides and nutrients. The watershed of Heiabekken is 4.6 km^2. More than 70 % of the area is arable land, the other main part not cultivated is forest (20 %). The area is a dissected marine landscape with moraine ridges especially in the upper and eastern part of the watershed. The upper part of the watershed contains marine beach deposits with permeable, sandy soils. The frequency of less permeable soils with higher content of clay and silt increases with decreasing distance from the sea. The arable land is dominated by Stagnosols (44 %), Gleysols (22 %) and Arenosols (18 %). Seven other soil groups represent smaller areas among them Cambisols have the largest coverage (7 %). The area is situated close to the coastline and has mild winters and early springs compared to the general climate of Norway. From November to February normally the precipitation is snow but because of mild periods permanent snow is rare. Because of early spring and suitable soil for agriculture, production of vegetables and potatoes are important. In addition to vegetables, cereals are the most frequently grown crops in the area. This region represents one of the most intensively cultivated areas in Norway and the use of pesticides and nutrients is important. More than 90 % of the crops are sown in spring.

2.3.   Micro-topographical maps

To identify vulnerable areas micro topographical maps were developed. These maps show depressions in the field where water is collecting after heavy rain or in springtime with snow melt and frost in the ground. Observations from farmers in the area show that water disappears within few days when the frost in soil disappears. The hypotheses are that the risk of leaching from these areas is larger as vertical transport of pesticides is water dependent with water as a carrier of the pesticides. A digital elevation model with a horizontal resolution of 5m was used to derive a map showing the terrain as a combination of elevation and hill-shade.

2.4.   Pesticide simulation with MACRO_GV and digital soil data

MACRO_GV (Stenemo et al., 2007), is based on the MACRO model (Larsbo et al., 2005). One requirement when developing the tool was that it should only require easily available data for model parameterization, such as texture and soil organic carbon content. The model is parameterized using a combination of
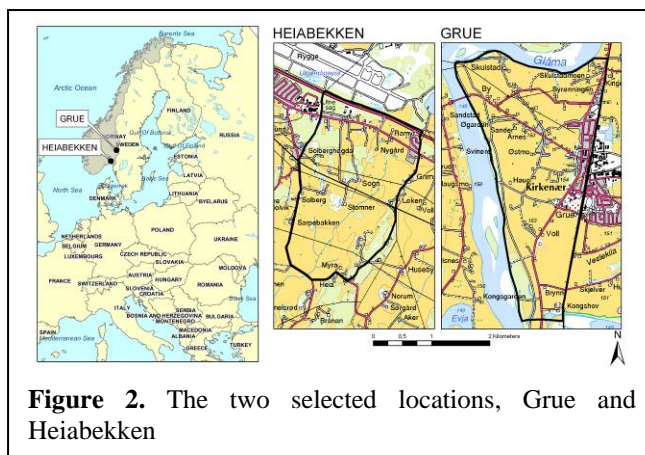
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pedotransfer functions (e.g. Wösten et al., 1998; Jarvis et al., 2002; Bergkvist and Jarvis, 2004), default parameter values and reasonable worst-case parameter values. A pesticide database is linked to the tool. The pesticide database is contained in a stand-alone access database. The tool access data from the database and allows the user to select an active ingredient.

The simulation set-up and output from the tool is similar to the FOCUS (2000) groundwater scenarios. Output consists of simulated average yearly leaching concentrations (20-year simulation) at one meter depth, and the long-term average concentration. The tool provides site-specific simulation scenarios that provide a measure of the risk of pesticide leaching for locations where little input data are available. The tool produces results in a fixed format. This makes it easier to compare and communicate simulation results between various end-users.

For both areas digital soil data exist. In Norway there is an ongoing program for detailed soil mapping of agricultural land in the scale of 1:5000. The classification system used is based on World Reference Base for Soil Resources (IUSS 2006). Relevant soil parameters needed for the MACRO-GV simulations were extracted from the Norwegian Soil Data Base for 13 soil types in the Grue area, and for 18 soil types in the Heiabekken area.

2.5.   Pesticide simulation with a meta-model of MACRO linked with digital soil maps and presented with GIS

A meta-model of the MACRO model (Larsbo et al., 2005) was built as a look-up table. Simulations to populate the look-up table were run with MACRO for each location (Grue and Heia) for 42 hypothetical pesticides and two different crops and application dates (spring and autumn sown crops with pesticide application in spring and autumn). An application rate of 1 kg active ingredient/ha was used. 42 different combinations of pesticide topsoil half-life (1-100 days) and the distribution coefficient K_{oc} (3-1000 g/cm^3) were used. K_{oc} express the ratio between the sorbed and dissolved pesticides in soil, adjusted for the content of organic matter. The simulations were run for 31 different soil types. The target output was either the average leaching concentration at one meters depth, or the median of the pesticide concentration in the bottom model layer, depending on the bottom boundary condition. In order to estimate simulation results for a real pesticide, the results in the look-up table are used for bi-linear interpolation of the simulation results with respect to pesticide topsoil half-life and K_{oc}. The results are then scaled with the actual dose of the pesticide, assuming a linear isotherm.

Simulations were parameterized using mostly the same routines and assumptions as in MACRO_GV. The bottom boundary condition varied depending on the different soils' hydrological characteristics and was for all but one soil set to either unit hydraulic gradient or as no flow. For one soil a groundwater table was modeled in the profile with percolation regulated by the water table height. In MACRO_GV only unit hydraulic gradient is used at bottom boundary condition.

Based on the hydrological class and simulation results (Table 2), the simulation results were classified into four risk classes (no, low, moderate, high risk).

The risk classes for the 31 soil types were linked into a geographic information system containing the soil map. Risk maps were produced for commercial compounds and dose. When a commercial compound contained several active ingredients, separate maps were made for each of the ingredient otherwise the maps show risk for the compound If a soil polygon was composed of more than one soil type, the risk for the soil with the highest risk is showed on the map.

Risk maps for 30 compounds used in cereals and 21 compounds used in potatoes were produced, both with the normal dose and some of them in addition with reduced dose.

2.6.   Evaluation by farmers

The information provided by the project was presented to two focus groups of farmers. The objective of the focus groups was to gain major insight from these focus group talks if such tools are to be used by farmers and if they could find positive net use values. Another question was to get insight in the farmers' attitude to different presentations and user interface.

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3. RESULTS

3.1. Micro-topographical maps

For both areas topographical maps were developed. From these maps depressions could be identified (Fig. 3). Depressions were found more frequently at Grue than Heiabekken because of the generation of the area. The depressions represent areas where water is gathering after heavy rain or in spring when the snow is melting and the ground is still frozen. The risk of leaching to groundwater is high in these areas because of enhanced vertical transport of water which is a carrier of pesticides. The map show the shape of the field based on level and shadow.

3.2. Simulations with MACRO_GV

The results from the simulations with herbicides used in spring cereals are given in table1-3. The applied dose of the pesticide represents the highest legal dose (NAD). The risk classes are based on the combination of simulated concentration and hydrological classes of the soil type. Herbicides were the group with highest risk of leaching.

Figure 3. Micro-topographical map of Grue

Table 1 Soil types and selected properties

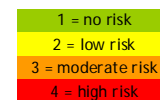|	ATm4	AFs5	FOs5	TLt5	KMk5	KGl5	KLr5	TKi5	THg5
WRB-unit	Haplic Arenosol	Endogleyic Arenosol	Gleyic Fluvisol	Umbric Fluvic Cambisol	Endostagnic Fluvic	Fluvic Cambisol	Endostagnic Fluvic	Fluvic Stagnosol	Fluvic Stagnosol
Org. C (%)	1-2	2-3	3-5	>5	2-3	1-2	2-3	2-3	2-3
Influence of water	None	Gr.w. >50cm	Ground w.	Surface w.	Surf.w. >50cm	None	Surf.w. >50cm	Surface w.	Surface w.
Hydrological class	A	B	B	B	B	A	B	B	B

Table 2 Risk of herbicide leaching to groundwater from different soil types according to table 1

Grue - Spring cereals

Trade name	Active ingredient	ATm4	AFs5	FOs5	TLt5	KMk5	KGl5	KLr5	TKi5	THg5	Dosage (NAD)
Actril 3-D	Ioxynil	1	1	1	1	1	1	1	1	1	
	Dichlorprop - P	4	4	4	4	4	4	4	4	4	3 l/ha
	MCPA	1	1	1	3	2	1	1	1	1	
Ally 50 ST	Metsulfuron - methyl	4	3	3	3	3	4	3	3	3	0.012 kg/ha
Ally Class 50 WG	Metsulfuron - methyl	4	3	3	3	3	4	3	3	3	0.05 kg/ha
	Carfentrazone - ethyl	4	3	3	3	3	4	3	4	3	
Ariane S	Fluroxypyr 1-methylheptylester	4	3	3	3	3	4	3	4	3	2.5 l/ha
	Clopyralid	4	4	4	4	4	4	4	4	4	
	MCPA	1	1	2	3	3	1	1	1	1	
Roundup ECO	Glyphosate	1	1	1	1	1	1	1	1	1	4 l/ha
Express	Tribenuron - methyl	4	3	3	3	3	4	3	3	3	1 tabl./0.5 ha
Harmony Plus 50 T	Thifensulfuron - methyl	1	1	1	1	1	1	1	1	1	0.015 kg/ha
	Tribenuron - methyl	4	3	2	2	3	4	3	3	2	
Hussar	Mefenpyr - diethyl										0.2 kg/ha
	Iodosulfuron - methyl	3	2	2	2	2	3	2	2	1	
MCPA 750	MCPA	4	1	3	4	4	4	1	4	3	4 l/ha
Optica Mekoprop - P	Mecoprop - P	4	2	3	3	3	4	3	3	2	3 l/ha
Primus	Florasulam	1	1	1	1	1	1	1	1	1	0.1 l/ha
Puma Extra	Fenoxaprop - P - ethyl	1	1	1	1	1	1	1	1	1	1.2 l/ha
	Mefenpyr - diethyl										
Starane	Fluroxypyr 1-methylheptylester	4	4	4	4	4	4	4	4	4	2 l/ha

Table 3 Risk classes based on hydrology and pesticide concentrations

Hydrological class	Concentrations (µg/L) simulated with MACRO_GV				
	< 0.001	0.001 - 0.01	0.01 - 0.1	0.1 - 1	> 1
A	1	2	3	4	4
B	1	1	2	3	4
C	1	1	1	1	1

1 = no risk
2 = low risk
3 = moderate risk
4 = high risk

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Hydrological class A: Well-drained soils (natural drainage) with no drains or no gley features within 100 cm depth

Hydrological class B: Moderately well drained soils with gley features within 100 cm depth and poorly drained soils with gley features directly below the topsoil, or soils that have drains

Hydrological class C: Poorly drained soils formed on massive clays or shallow soils on hard rocks.

3.3.   Simulations with the meta-model of MACRO and GIS
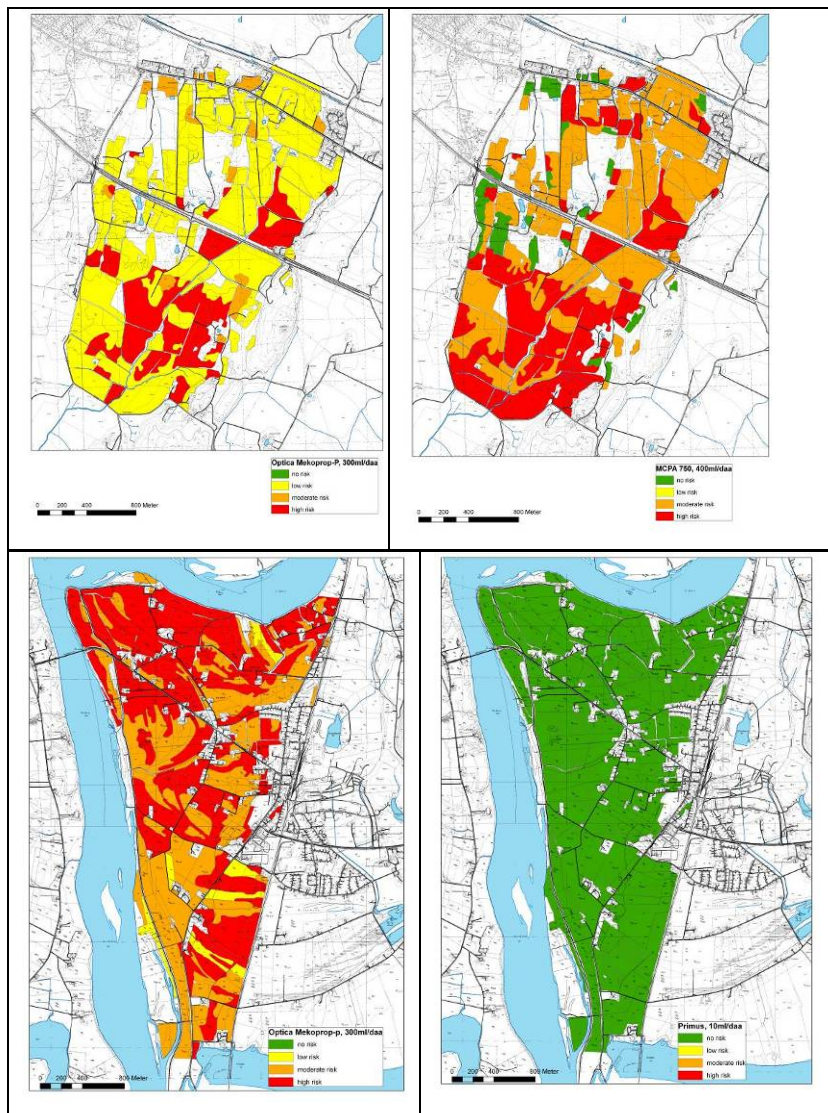
Risks maps for different herbicides in the two areas are shown in figure 4.

They indicate strong variation between different compounds. Besides they show different risk classes for different soil types. Comparing the results from MACRO_GV with the meta-model of MACRO show differences (data not presented). This can be explained by the difference in the two models to handle sorption. The MACRO_GV uses the Freundlich equation for the calculation of the concentration in the solution while the meta model of MACRO uses linear relationship between concentration in soil and the solution . In our project we decided to harmonize the result from the simulations with the risk maps by using the results from the MACRO_GV for producing the risk maps to avoid confusion.

3.4.   Evaluation by the farmers

The focus group responses indicated that farmers were interested in the project and its results. However, they were concerned about the user interface, which in the pilot version consisted of maps and

Figure 4. Risk maps of Heiabekken and Grue

risk tables on paper. The farmer's opinion was clear that the maps should be computer based, and preferably well integrated with other existing planning tools. Farmers were also concerned about the reductions in the available pesticides, limiting their choices and possibly reducing the value of the risk information provided by the project. In particular in Heiabekken, farmers were clear that environmental measures should have minor costs as the economic surplus from the farming activities were already close to what they could bear to continue farming. The responses in Grue were a bit less cost oriented and with a stronger focus on the environmental issues. A possible reason for this is that in Grue, several farmers fetched their drinking water from aquifers underneath their own fields. As one farmer phrased it: «If I am to die from drinking, it should not be from drinking water». Both focus groups were clear that in situations with differing pesticide leaching risks on different plots, tools that quickly identify which pesticides that can be used across all plots on a farm

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is needed. This response was related to the time costs of having to clean spraying equipment if another pesticide were to be used. A major insight from these focus group talks is that if such tools are to be used by farmers, they must have positive net use value for farmers. To reduce farmers' (time) costs, and hence increase the net benefits of the project, pesticide risk maps must be well integrated with existing planning tools.

4. DISCUSSION AND CONCLUSIONS

Deriving a micro-topographical map depends on appropriate elevation data. The elevation models used in this project did not allow deriving a dataset containing real sinks because of precision and quality issues. But the derived map can be used to identify depressions visually. By using data such as data from airborne laser scanning it would be possible to detect such areas automatically.

The risk maps produced in this pilot-project are restricted to a selection of products and doses. It would be desirable to develop an interactive (web-) application allowing specifying which arbitrary preparations and doses the map should show the specific risk of.

Even if the project areas were small, the number of soil types was large. Coupled with many pesticides, different application doses and different crops, the simulations were very time consuming. To be able to run this system for larger areas, it is probably necessary to reduce the number of soils. Instead of running the model for each individual soil type, it is possible to use the WRB-unit level (World Referance Base for Soil Resources, 2006) and geological origin to aggregate soil properties.

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