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ASSESSING THE IMPACT OF AGRICULTURAL LAND USE CHANGES ON WATER QUALITY

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ABSTRACT

To study and predict environmental impacts of land use changes on water quality we conducted different types of lysimeter experiments. All of them are linked to representative experimental catchment areas in the field. This allows the verification and extrapolation of lysimeter results. The objective of this paper is to discuss a strategy for using and scaling-up of lysimeter results to a field and catchment scale. It will be shown that the N-loss determined with lysimeters falls within the variation of N-balance based model calculations, and also within ground water recharge rates calculated with models commonly used in hydrology. Extrapolation of lysimeter data to a catchment with similar soils provides a reliable basis for estimating the N-leaching caused by a change in agricultural land use. On the basis of the N-loss from the soil and the N-load of the stream, the calculations show that an increase in the proportion of one year rotation fallow from 10 to 25% results in nearly a 10% increase in the N-load of the stream. However, from the point of view of protecting drinking water quality, rotation fallow for one year is not recommended because of the resulting intensified leaching of nitrates. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Land use change; lysimeter experiment; nitrogen; scaling-up; set-aside; water balance

INTRODUCTION

Recent studies have shown that in Germany agriculture is directly responsible for more than 50% of the nitrogen (N) leached into streams and rivers. This takes place primarily through a diffuse soil - ground water - surface water pathway (Novotny, 1995).

German reunification in October 1990 brought about a transformation in the structure of agriculture in the former GDR. East Germany became a part of the European Community and subject to the Union's common agricultural policies. These policies call for reducing agricultural overproduction. In the eastern part of Germany as much as 10% of the 6.2 million hectares of previously intensively farmed areas were set aside by 1991.

Past intensive land use resulted in an accumulation of nutrients and agrochemicals in the soil. This represents a significant potential risk for the quality of both surface and ground waters (Hekstra, 1995). This potential environmental problem becomes more acute if it is taken into account that in the eastern part of Germany most ground water recharge takes place in agricultural areas and that more than 70 % of the drinking water supply comes from ground water. Therefore, it is of vital interest to know the quality and quantity of seepage water which leaves the root zone, then enters the aquifer and finally the surface water system. This knowledge will help to define changes in land use and farming methods which can contribute to an improvement in water quality.

MATERIAL AND METHODS

In the last few years a lot of work has been done in Germany to describe the pathways of pollutants from non-point sources. At this time rough estimates of nutrient budgets (especially nitrogen and phosphorus) are available for the most important river systems. But there is a gap in our knowledge about the assessment of various land management methods on water quality (Mohaupt and Behrendt, 1997). Solving the problem with investigations of whole river systems only is not possible, because they are very heterogeneous and a separation of important impact factors is almost impossible. In our opinion it is better to work on different scales and try to explain the relevant processes.

For this reason we carried out lysimeter trials to get information on how different land management methods influence the amount and quality of seepage water. In the next step we tried to find this result in a field and a (small) catchment scale, because we are interested in how different types of land management influence the quality of ground water (after leaving the root zone) and surface water (after transport in the saturated zone). At the same time we tried to validate the lysimeter data at the field and catchment scale and to use the measured data for comparison with, and improvement of, models. In this paper we will give an example of this strategy. Because N (especially nitrate) is the most important criterion for drinking water quality in Germany we will demonstrate the results for this nutrient.

RESULTS

Lysimeter scale

Lysimeter studies

The UFZ Centre for Environmental Research operates 200 lysimeters at 6 lysimeter stations and at 3 sites (Falkenberg, Colbitz, Brandis) in typical regions of the Elbe river catchment (Meissner *et al.*, 1998a). All lysimeter experiments are linked to experimental catchment areas in the field to establish and verify extrapolation domains. The UFZ Lysimeter Research Station in Falkenberg represents the Elbe catchment in the northern regions of the states of Saxony-Anhalt and Brandenburg. One hundred and twenty non-weighable lysimeters each with a surface area of 1 m^2, a total depth of 1.25 m and free drainage were constructed in 1983. The lysimeters were filled with disturbed soil profiles (sandy loam, sand, loam, loess) commonly found in the catchment area of the Elbe river and the northern part of Germany.

In the spring of 1991 a lysimeter trial, originally designed in 1983 to maximize yields, was adapted to these new conditions in agricultural land use. The purpose of the trial was to investigate the impact of the structural changes in agricultural land management on the water and solute balance. The seepage water from the lysimeters was collected continuously in storage containers and then pooled to obtain a mixed sample for every month.

The land use change experiments included 30 lysimeters:

- 10 lysimeters were treated as permanent fallow (beginning on August 1, 1991);
- 10 lysimeters were treated as rotation fallow for one year (the first fallow period was implemented from August 1, 1991 to July 31, 1992) before resuming intensive crop cultivation;
- 10 lysimeters were treated according to Best Management Practices (BMP), whereby fertilization and irrigation is done in accordance with the plant's requirement for nutrients and water as well as ecological and economic demands.

The N-load (Σ NO_3-N + NO_2-N + NH_4-N) in the seepage water from the three lysimeter groups is shown in Figure 1.

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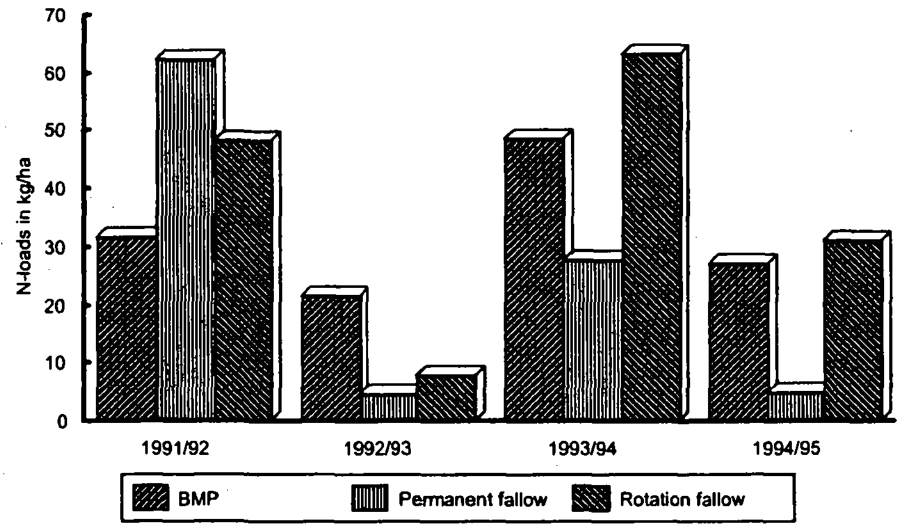

Figure 1. Annual N-load in the seepage water as a function of the farming scheme.

The lysimeter tests furnished proof that restricting agricultural use of areas, previously farmed intensively, by converting them into permanent fallow or rotation fallow will result in measurable changes in the water and solute balance within a short period of time (Meissner *et al.*, 1998b). In this respect it is interesting that in year 1991/92 a significantly increased loss of nitrate occurred in the set-aside lysimeters as compared with BMP. This is due to the fact that the plant stands, which were newly establishing themselves on the fallow treatments, withdraw less nitrogen. The surplus of nitrogen contained in the soil originates from previous intensive cultivation and cannot be utilized sufficiently by non-agricultural plants. Consequently, this nitrogen is leached with the seepage water. Due to the depth of the lysimeters used in the test and a lack of mineral fertilization, the set-aside treatments showed a clear reduction of nitrate leaching as early as 1992/93 compared with BMP. In the case of the permanent fallow, this trend continued in 1993/94 and 1994/95. The higher level in 1993/94 was due to increased mineralization caused by the weather. In contrast, the rotation fallow was stopped and intensive farming resumed. Intensive farming was associated with a considerable increase in nitrate leaching in the test years 1993/94 and 1994/95 due to resumed mineral fertilization and soil cultivation which contribute to increased mineralization. It is important, with regard to the protection of the ground water resources, that the highest nitrate leaching loss was measured after four years of trial under rotation fallow, and even in the case of permanent fallow the total amounts of leaching nitrate were approximately 23% below the values for BMP.

Using the lysimeter data for modelling

The simulation model CANDY (Carbon and Nitrogen Dynamics), which was developed in the UFZ, describes all important soil processes concerning the C-N- dynamics in rural landscapes (Figure 2). Important inputs are soil physical properties, meteorological data and management information. The model works in daily time steps and produces outputs concerning relevant ecological information (Franko, 1996). Because lysimeters produce real data about the leaching process they are ideally suited for the validation of models. Since 1992 we have conducted special investigations to compare measured and calculated water and solute balances. A comparison of measured and calculated N-loads for two agriculturally used lysimeters (replications with the same crop rotation) from the Lysimeter Research Station in Falkenberg is given in Figure 3.

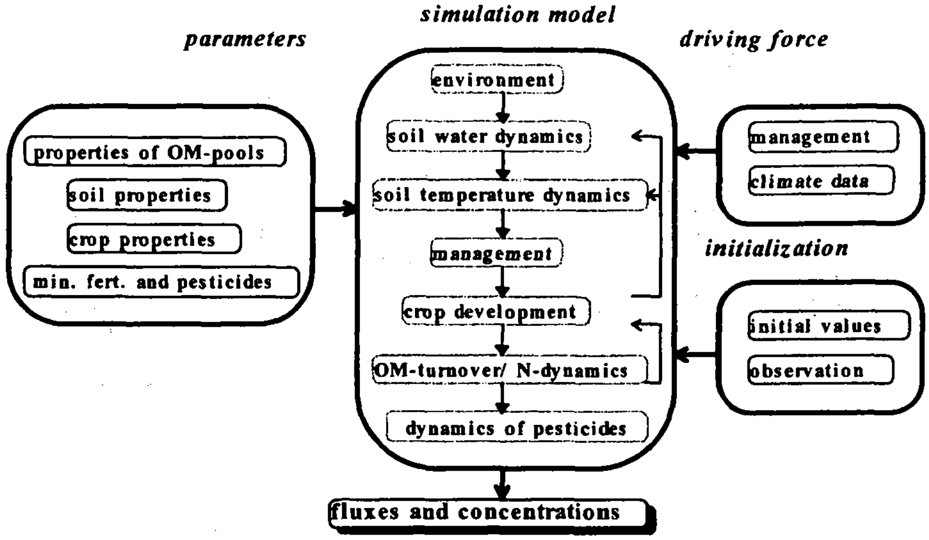

Figure 2. Structure of the simulation model CANDY (according to Franko, 1996).

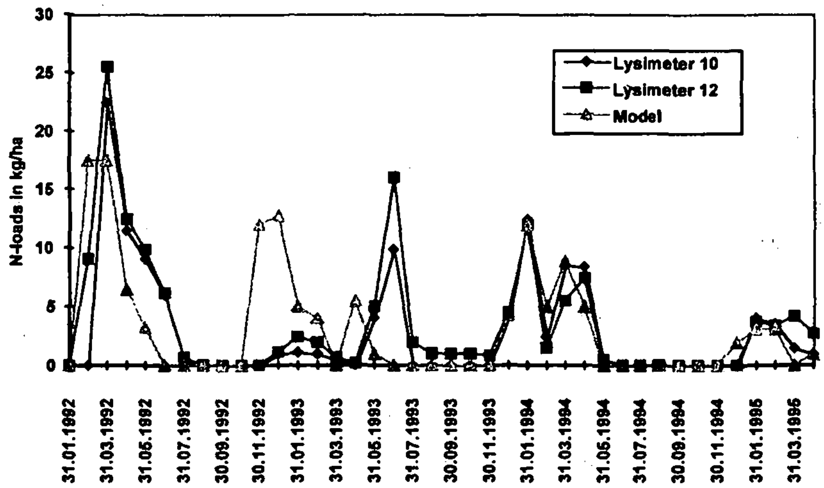

Figure 3. Comparison of N-loads measured with lysimeters and calculated with the simulation model CANDY.

Comparing the N-loads measured with the lysimeters and calculated with CANDY reveals differences in the years 1992 and 1993. Since 1994 the N-loads calculated with CANDY fall within the range of values observed in lysimeters.

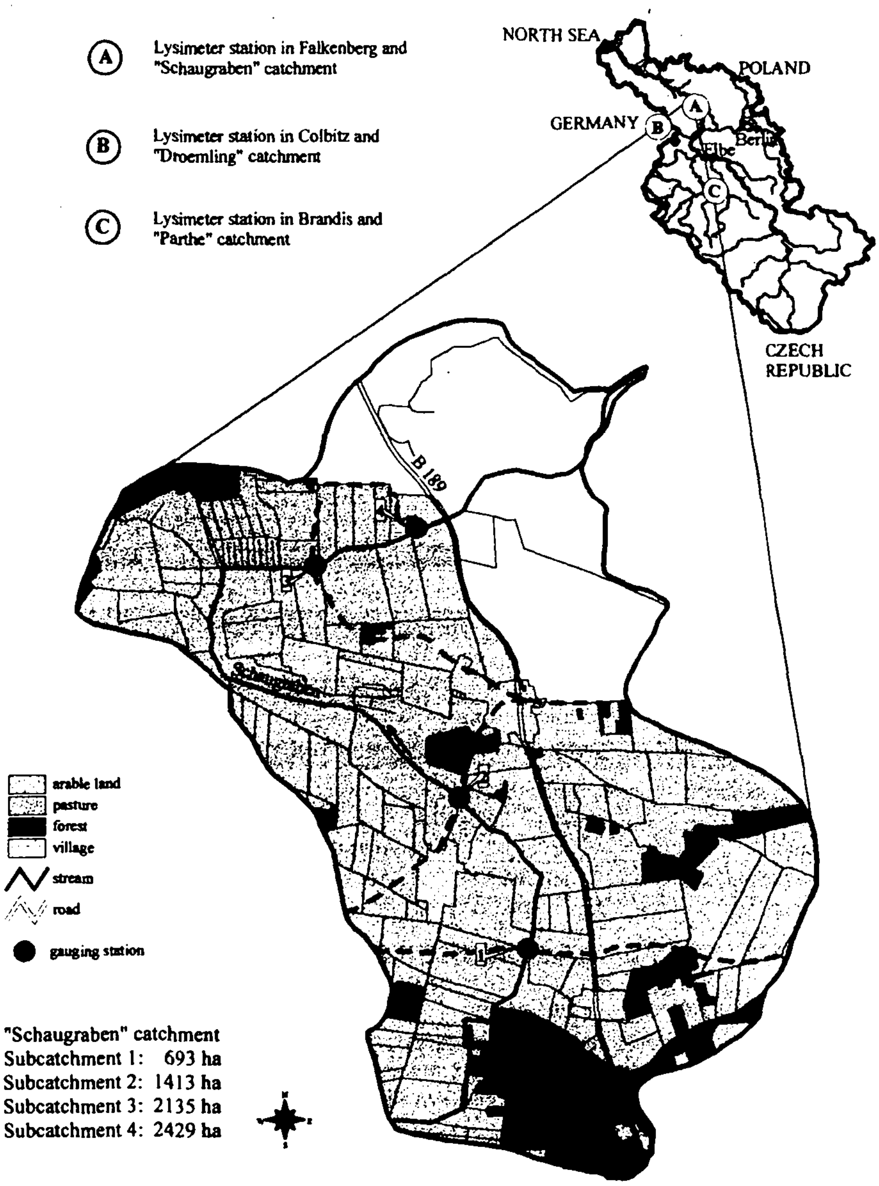

Figure 4. Geographical location of the experimental catchment area 'Schaugraben' inside the Elbe catchment and the UFZ managed lysimeter stations.

Field and catchment scale

Schaugraben catchment

With the aim of scaling-up and of calculating the effects of set-aside under natural conditions, the results of the lysimeter studies were extrapolated to a small catchment area about 15 km from the lysimeter station, which corresponds to the location of the lysimeter both in relation to meteorological factors as well as in relation to pedological parameters. The main stream in this experimental area is called the Schaugraben. The Schaugraben is a tributary of the Elbe river in north-east Germany (Figure 4). The basin is largely agricultural with the exception of the forested headwaters. The catchment area was subdivided into four partial catchment areas. Four gauging stations were equipped; discharge and water quality were measured twice monthly at each site from October 1992. At the outlet of the Schaugraben stream (subcatchment 4) discharge and water quality have been monitored automatically since May 1997. Historic and recent land - use patterns (i.e. forest, pasture and arable land along with type of crops and fertilization regime) in the Schaugraben catchment have been quantified since 1991 and mapped in a GIS. The type of land use is an important consideration when attempting to quantify and predict nitrate leaching. Figure 5 gives an overview of land use change in the experimental catchment after reunification of Germany. The increase of the share of rotation fallow for one year is important. This kind of land use was unknown under the former conditions of co-operative farming.

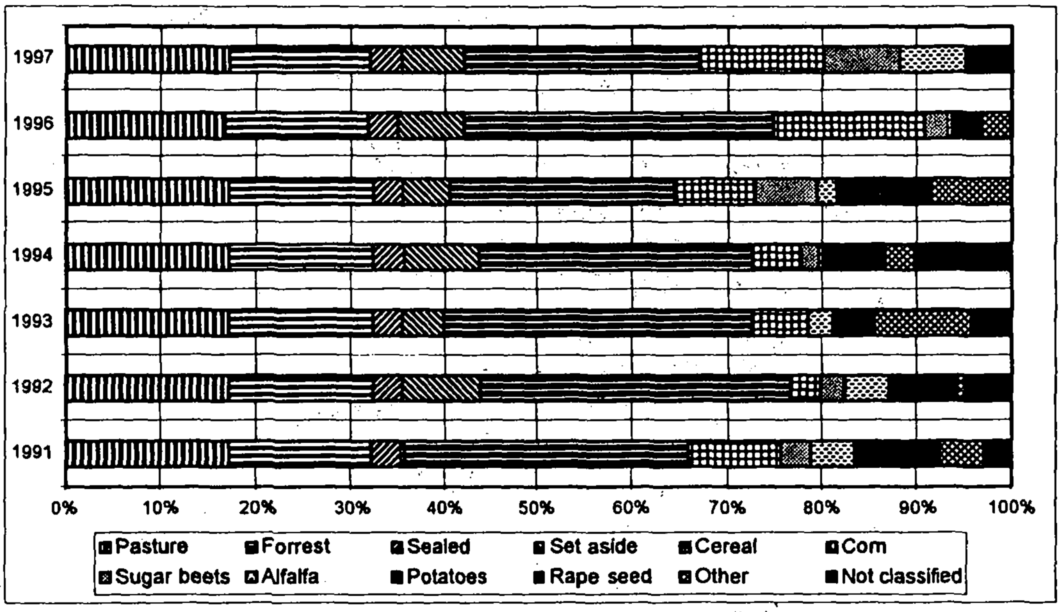

Figure 5. Land use changes in the experimental catchment Schaugraben.

Comparison of lysimeter and field investigations

The scaling problem is very important in the comparison of lysimeter and field results. In addition to the lysimeter measurement we carried out special field investigations in catchments with compatible soils. As mentioned above we found a considerable increase in nitrate leaching in the lysimeter after stopping the rotation fallow and resuming intensive farming (compare Fig. 1; years 1992/93 and 1993/94). On the field scale we measured the plant available nitrate content in the soil (Nmin) every month. Figure 6 shows that after a fallow period and a subsequent planting of corn on this field in May 1994 the Nmin content in the soil increased. In the future this will lead to an increase in nitrate leaching. It can be shown that the effect we measured in the lysimeter occurs on the field scale, too.

Application of lysimeter results to the experimental catchment

Water balance. As a precondition for extrapolating the results of the lysimeter trials, a comparison was made between the amount of seepage water measured in the lysimeters and ground water recharge in the area as calculated with models commonly used in Germany (Table 1). As expected, discrepancies were found between the calculated values and the values obtained with the lysimeters. But the seepage water quantities determined with the lysimeter fall within the range of the calculated ground water recharge rates.

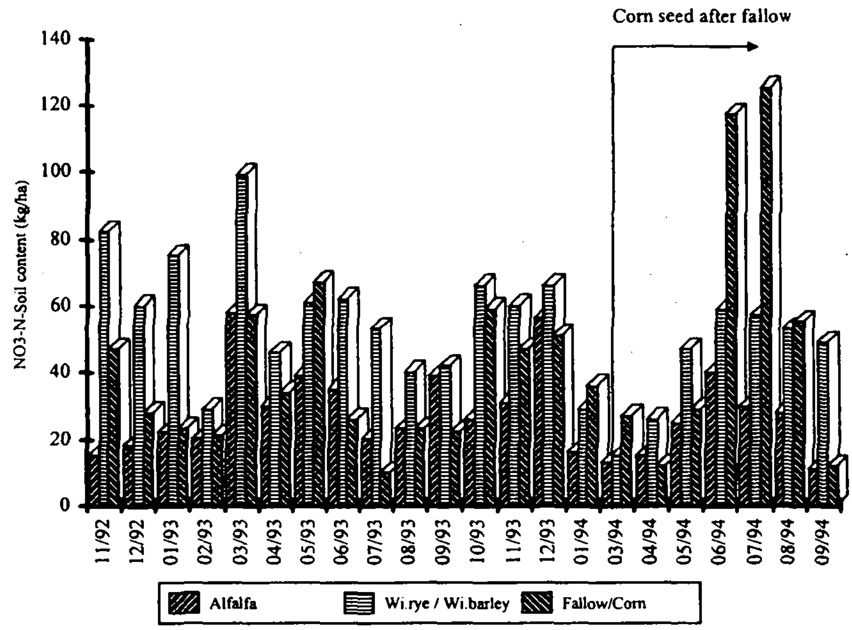

Figure 6. Comparison of soil NO_3-N (0-90 cm) of two cropped sites and a fallow site after the resumption of intensive farming.

Table 1. Comparison of results from long-term lysimeter studies and calculated mean annual ground water recharge in the Schaugraben catchment

Reference	Arable land** (14.83 km²)	Pasture** (5.23 km²)	Forest** (3.74 km²)	Σ Ground water recharge** (23.80 km²)
Calculated recharge				
Model "RASTER" [1)]	-	-	-	125
Bagrov-Glugla* [1)]	95	-1	-1	93
Renger-Wessolek [1)]	87	15	11	113
Doerhoefer-Josopait [1)]	96	16	11	123
Long-term lysimeter studies	72	23	2	97

*Long- term mean precipitation at the Falkenberg lysimeter station: 504 mm
Long-term mean evaporation rate at the Falkenberg lysimeter station: 565 mm
** Ground water recharge in mm
[1)] See References

Solute balance. On the basis of the results of the lysimeter studies and the land use in the catchment, an estimate of N-loss from the soil was made for several hydrological years. We compared these results with a GIS added version of a N-balance model (Table 2), developed and adapted from Dannowski (1997). The scheme of the model and the structure of the GIS-based calculation are shown in Figures 7 and 8.

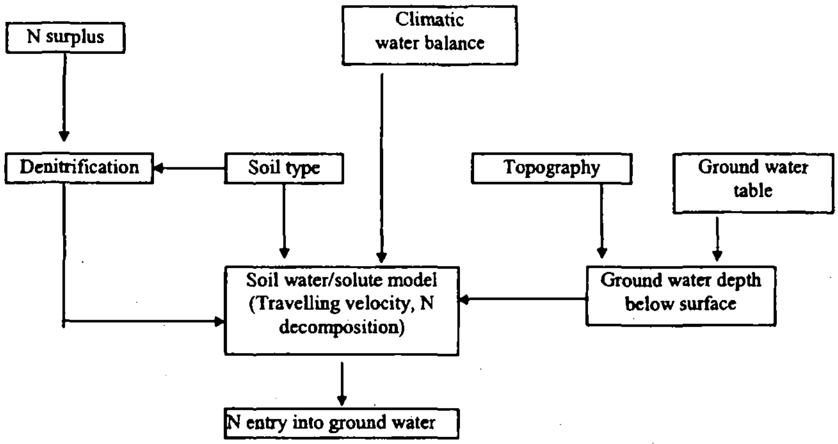

Figure 7. Schematic of modelling the nitrogen (nitrate) entry from agriculturally used areas into ground water (Dannowski, 1997).

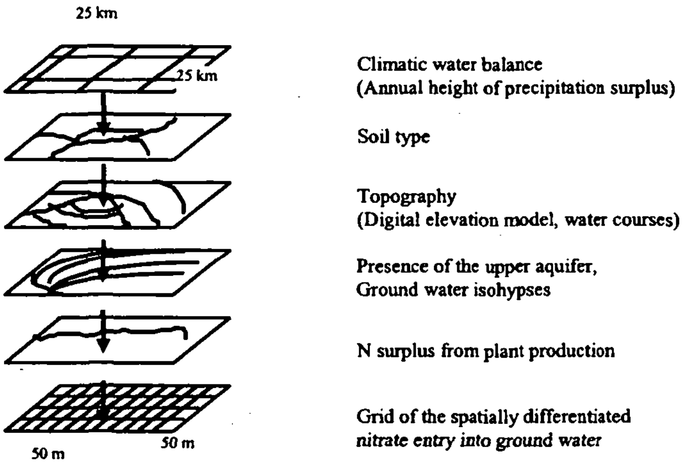

Figure 8. GIS-based overlaying information to analyse nitrate entries into ground water on catchment scale (Dannowski, 1997).

The exactness of N-balances depends on the information about the N-input and N-output. For this reason a reliable exchange of information between farmers and scientists is necessary. This is ensured for the experimental catchment but often not for unknown areas. If we compare the N-loss calculated with different methods it shows a moderate correspondence. It seems that the denitrification is overestimated in the model, because it is focused on the top soil (soil depth of 0.5 m) and is often higher than the N-loss measured in the lysimeters with a depth of 1.25 m. But the N-loss determined with lysimeters falls within the variation of N-losses calculated with the model. They are also comparable to ground water recharge rates calculated with models commonly used in hydrology. Therefore, we assume that leaching of nutrients measured with lysimeters reflects the conditions in the catchment area with sufficient accuracy to allow extrapolation.

Table 2. Comparison of N-loss from the soil for the different subcatchments of the Schaugraben catchment based on model calculations and lysimeter results (N-loss in kg/ha).

Subcatchments of the Schaugraben	SC1 612 ha	SC2 800 ha	SC3 793 ha	SC4 210 ha
N-balance model				
N surplus at the soil surface 1993	28	46	40	12
N surplus at the soil surface 1994	19	35	42	33
N surplus and denitrification factor*) for the upper soil 1993	16	26	20	4
N surplus and denitrification factor*) for the upper soil 1994	8	19	22	22
Lysimeter results				
Measured N-loss 1993	46	43	42	40
Measured N-loss 1994	17	26	27	11

*) according to Köhne and Wendland (1992)

Comparison between N-loss from the soil and N-load of the stream
Based on annual results of the lysimeter studies (N leached in drainage water) and the actual land use in the catchment (crops planted, fallow, pasture, forest) an estimation of N-loss from the soil was made for each year. Based on the discharge measured at 4 gauging stations and analyses of its N-content, the annual load was calculated for the whole Schaugraben catchment (Table 3).

Table 3. Comparison of estimated N-loss and calculated N-load of the Schaugraben.

Year*)	Annual precipitation (mm)	N-loss from the soil (kg)	N-load of the stream (kg)	Differences N-loss/N-load (kg)
1993	701	57760	26610	31150
1994	762	107070	76350	30720
1995	505	61070	28080	32990
1997	434	22950	7950	15000
1998	650	42470	17150	25320

*) 1996: no data due to long and severe frost period

The N-loss from the soil and N-load of the stream at the bottom of the catchment reveal a difference of between 29 and 65%. The observed reductions agree reasonably well with postulated - but at this time not measured - factors in the literature (Behrendt, 1995). The most important reason for these differences is probably the highly variable hydrological regime. At present the whereabouts of these amounts of N cannot be determined precisely. In future work we will start experiments with conservative tracers (Cl and Br), stable isotopes (^{15}N, D_2O) and natural isotope signatures (^{2}H, ^{18}O, ^{15}N, ^{34}S) to explore the pathways and transformation of N during transport from soil surface via ground water to the surface water.

On the basis of the above findings we estimated the effect of rotation fallow (only this kind of fallow was present in the experimental catchment) on the N-load of the Schaugraben. An increase in the proportion of rotation fallow from 10 to 25% would have raised the N-load in the Schaugraben stream by about 10%.

CONCLUSIONS

Changing previously intensively farmed agricultural areas to fallow will result in increased deep percolation, at least in the first year of set-aside. In addition, extra leaching of N contained in the soil will occur.

From the point of view of protecting drinking water quality, one year rotation fallow is not recommended because of the resulting intensified leaching of nitrates.

Lysimeters allow a realistic simulation of a wide range of scientific and practical questions on the small and medium scale. Lysimeters are ideal research facilities to explore environmental impacts of land management, to develop and test simulation models and to design sound and feasible management practices.

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