

Effects of natural and anthropogenic factors on nitrogen fluxes in agricultural soils: a modelling study in the Saale River basin (central Europe)

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Abstract After validation of nitrogen (N) dynamics in two mesoscale sub-basins of the Elbe, simulation experiments for analysing N leaching to groundwater were performed for a set of representative conditions using the SWIM model in the Saale River basin (23 687 km²), a tributary of the Elbe River. The area was subdivided into five climate zones, and nine representative soil classes were chosen. The basic rotation and fertilization schemes were created using information obtained from environmental agencies. In addition, the effects of fertilization rates were studied. The ranges of simulated N fluxes for the basic rotation and fertilization schemes are comparable to available regional estimates, and differences between sub-regions are plausible. The relative importance of natural and anthropogenic factors affecting N leaching to groundwater for the Saale River basin was as follows: (1) soil, (2) climate, (3) fertilization rate, and (4) crop rotation. The simulation experiments provide a basis for a metamodel approach, which aims at rapid water quality assessment of large regions.

Key words diffuse pollution; central Europe; integrated modelling; land use; nitrogen fluxes; nitrogen leaching to groundwater; non-point source pollution; river basin; water quality

INTRODUCTION

Non-point or diffuse sources of nutrients in the rural landscape are one of the most significant causes of groundwater pollution in Europe. Understanding and quantification of the impacts of different land use and land management practices and natural conditions (e.g. fertilization rate and time of application, soil, climate and topography) on groundwater pollution are needed to assess the effects of measures aimed at the reduction of diffuse pollution. Integrated models coupling hydrological, biogeochemical and ecological processes at the river basin scale are best suited to investigate the complex chain of interrelated factors defining nitrogen leaching to groundwater. The simulation experiments performed for the Saale River basin (central Europe), one of the main tributaries of the Elbe River, had two main objectives: (a) to evaluate factors influencing nitrogen leaching to groundwater, and (b) to provide a basis for a fuzzy-rule based metamodel approach (Haberlandt *et al.*, 2001) for assessing water quality at a large scale. The modelling system SWIM (Krysanova *et al.*, 1998) was used as an integrated tool in our case study.

MODELLING SYSTEM

The modelling system SWIM (Soil and Water Integrated Model) (Krysanova *et al.* 1998) includes as its kernel, a continuous-time spatially-distributed model, which integrates hydrology, vegetation and nutrient (nitrogen, N and phosphorus, P) and sediment fluxes at the river basin scale. In addition, it includes an interface to the Geographic Information System GRASS, which allows the extraction of spatially distributed parameters including elevation, land use, soil type, and the routing structure for the model initialization. The model can be applied for mesoscale and large river basins (or regions) with an area of up to 25 000 km².

DESIGN OF SIMULATION EXPERIMENTS

The simulation experiments with SWIM described here were performed after the validation of N dynamics in two mesoscale sub-basins of the Elbe: the Stepenitz and the Zschopau (Krysanova & Becker, 1999; Krysanova *et al.*, 1999), and a successful hydrological validation for the whole Saale River basin (above gauge Calbe-Grizehne, 23 687 km²), which enters the Elbe 25 km south east of Magdeburg, Germany (51°57'N, 11°55'E). The simulation experiments designed for the metamodel approach had to incorporate a wide range of possible conditions, but the number of variants and the length of the time series had to be restricted. Therefore, not all combinations of natural conditions and management practices in the Saale River basin were considered in the simulation runs. The conditions incorporated in the simulations included a few climate conditions (represented by climate stations), soil classes (represented by soil types according to soil map BÜK-1000), elevation classes (represented by slope steepness), and agriculture practices (crop rotation and fertilization).

Five climate stations were chosen as representative for the region, based on a review of the long-term average annual precipitation and average temperature. Another condition for the inclusion of a station was that it has continuous data for the period 1961–1990. The five climate zones represented by the climate stations are listed in Table 1 and are ordered according to the annual precipitation which ranges from 460 to 940 mm. The altitude of the stations ranges from 164 m a.m.s.l. in Artern to 567 m a.m.s.l. in Hof-Hohensaas. The higher altitudes in the basin (up to 1100 m) were ignored, because most of the agricultural land is at lower altitudes; about 40% of agricultural land is located in areas lower than 200 m, 79% lower than 400 m, and 96.4% lower than 600 m. In general, agricultural land occupies about 70% of the Saale River basin.

Altogether, the cropland includes 34 soil types (BÜK-1000, Hartwich *et al.*, 1995), 23 of which occupy 96.7% of the total cropland area. Loess soils or soils from loess mixed with weathering products are the dominant types; rocky soils occur only in the mountains. The 23 agricultural land soils were subsequently classified into nine soil classes, according primarily to their field capacity and saturated hydraulic conductivity (Table 1). These nine soil classes represent a wide range of field capacities (32.3–49.8 vol. %), and a wide range of saturated hydraulic conductivity (0.4–41.1 mm h⁻¹).

Three rotation schemes, 10 years each, and three fertilization schemes represent a range of agricultural management practices (Table 1). The basic rotation and fertilization

Table 1 Classification of natural conditions and agricultural land management in the Saale River basin used for the simulation experiments with the SWIM model.

Climate zones, represented by climate stations						
No.	Station name	Station number	Altitude (m a.m.s.l.)	Average annual precipitation (mm)	Average annual temperature (°C)	
1	Artern	3402	164	460	8.64	
2	Erfurt	4200	316	503	8.01	
3	Gera-Leumnitz	4406	311	611	8.02	
4	Hof-Hohensaas	4027	567	732	6.46	
5	Bad Sachsa	3988	335	940	7.64	

Soil classes, represented by soil types (BÜK-1000)						
No.	Name of the main soil belonging to the class	Main soil ID	Other soils ID	Occurrence in arable land, %	Root zone field capacity (vol. %)	Saturated conductivity in root zone (mm h ⁻¹)
1	Floodplain soil from loamy-clay sediments	9	8, 49	7.0 + 4.4 ^a	39.3	5.0
2	Tschernosem from loess	36	–	13.8 + 0	39.7	9.9
3	Braunerde-Pelosol from weathering products	51	–	4.8 + 0	49.8	0.4
4	Braunerde from loess and weathering products	59	42	7.6 + 4.3	35.3	4.8
5	Tschernosem-Braunerde from loess	40	46, 11	5.1 + 4.5	36.9	17.5
6	Braunerde from loess and weathering products	56	48	6.4 + 5.7	37.5	9.0
7	Pseudogley-Tschernosem from loess	38	37, 41, 61, 64	3.9 + 12.2	38.6	20.5
8	Parabraunerde-Pseudogley from loess	43	44, 45, 53, 57	3.2 + 6.3	36.9	13.9
9	Braunerde from acidic rocks	55	–	4.3 + 0.	32.3	41.1

Rotation schemes										
No.	Crop sequence:									
	Year 1	2	3	4	5	6	7	8	9	10
1	po ^b	ww	sb	wr	set-aside	ww	wb	po	ww	ma
2	po	wb	ma	ww	wr	ww	ma	po	ww	ma
3	po	set-aside	sb	wr	set-aside	ww	wb	po	ww	set-aside

Fertilization schemes (fertilization rate in kg ha ⁻¹)							
No.	Winter wheat	Winter barley	Winter rye	Spring barley	Potatoes	Maize	Set-aside
1	30+60+30 N ^c 30+30 org N ^d	20+60+20 N 30+30 org N	20+60+20 N 30+30 org N	60+20+20 N 30+30 org N	140 N 30+30 org N	180 N 30+30 org N	0 N 0 org N
2	45+90+45 N 45+45 org N	30+90+30 N 45+45 org N	30+90+30 N 45+45 org N	90+30+30 N 45+45 org N	210 N 45+45 org N	270 N 45+45 org N	0 N 0 org N
3	15+30+15 N 15+15 org N	10+30+10 N 15+15 org N	10+30+10 N 15+15 org N	30+10+10 N 15+15 org N	70 N 15+15 org N	90 N 15+15 org N	0 N 0 org N

^a occurrence of the main soil plus occurrence of other soils;
^b po – potatoes, ww – winter wheat, wb – winter barley, wr – winter rye, sb – spring barley, ma – silage maize;
^c fertilization by mineral N;
^d fertilization by organic N.

schemes (schemes 1) were derived from the typical practices in the area (Roth *et al.*, 1998; Krönert *et al.*, 1999). Winter crops, as indicated in Table 1, are for the year when they are harvested. Two additional rotation schemes were applied; a more intensive rotation (scheme 2), which included two additional years of silage maize instead of one year of spring barley and one year of set-aside, and a less intensive rotation (scheme 3), which included two additional years of set-aside instead of one year of silage maize and one year of winter wheat.

The model rates of fertilization are crop-specific (Table 1). The grain crops (winter wheat, winter barley, winter rye and spring barley) are fertilized by mineral N three times, including once in autumn for winter crops, while for silage maize and potatoes the total annual amount is applied in one application, during the sowing (Roth, *et al.* 1998). In addition, organic fertilizer is applied using the following rules: for winter crops 30 kg ha⁻¹ of organic N is applied 23–43 days before sowing (depending on the previous crop) and 30 kg ha⁻¹ is applied at the beginning of March; and for summer crops 30 kg ha⁻¹ is applied at the end of October of the previous year and 30 kg ha⁻¹ is applied six weeks after sowing in the spring. Two other fertilization schemes were used in the model by increasing (scheme 2) or decreasing (scheme 3) the fertilization application rates by 50%, without changing the time of application.

The three rotation schemes and three fertilization schemes were combined. Note that the same fertilization scheme 1 combined with three different rotations assumes a different total amount of fertilizer applied in a 10-year period: a larger amount with rotation scheme 2, and a smaller amount with rotation scheme 3, compared to the amount with rotation scheme 1. This is due to a higher amount applied for the three-year maize in rotation scheme 2, and no application for three years of set-aside in rotation scheme 3.

Five elevation classes represented by topographic slope ranging from 0.2% to 10% were considered. Simulation runs were performed for 30 years, 1961–1990, for all possible combinations of five climate zones, nine soil classes, three rotation schemes, three fertilization schemes and five elevation zones, which produced $5 \times 9 \times 3 \times 3 \times 5 = 2025$ time series, each with a daily time step.

ANALYSIS OF RESULTS

Modelled daily water fluxes (direct runoff, interflow, groundwater recharge and evapotranspiration), and daily N fluxes (direct runoff and interflow losses, leaching to groundwater, uptake by plants, denitrification and mineralization), were aggregated to monthly, annual and average annual values, and analysed with respect to the different natural conditions and management practices. In this paper only the long-term average annual fluxes are discussed.

The combined effects of climate, soils, and elevation on N losses (considering lateral direct runoff, interflow, and leaching to groundwater) are shown in Fig. 1. In this example, only the basic rotation and fertilization schemes were considered. N losses for all soils increase with increasing precipitation from climate zone 1 to climate zone 5. Some soil classes (1–4) have low N leaching, which increases only slightly under wetter conditions (climate zone 5). N losses in direct runoff are small, they are important only for the less permeable soil classes 3 and 4 under wetter conditions. Total N losses with water fluxes are practically independent of elevation, however the elevation affects the redistribution of fluxes: N losses in interflow increase at higher elevation, and leaching to groundwater decreases (Fig. 1(b)), while the total amount remains practically the same. Consequently, the higher slopes were excluded from further analysis. Under the minimum slope assumption, the groundwater recharge and N leaching to groundwater for sandy soils increase only slightly, and more significantly for loess soils. This provides a sort of maximum estimate of N leaching to groundwater for all soils.

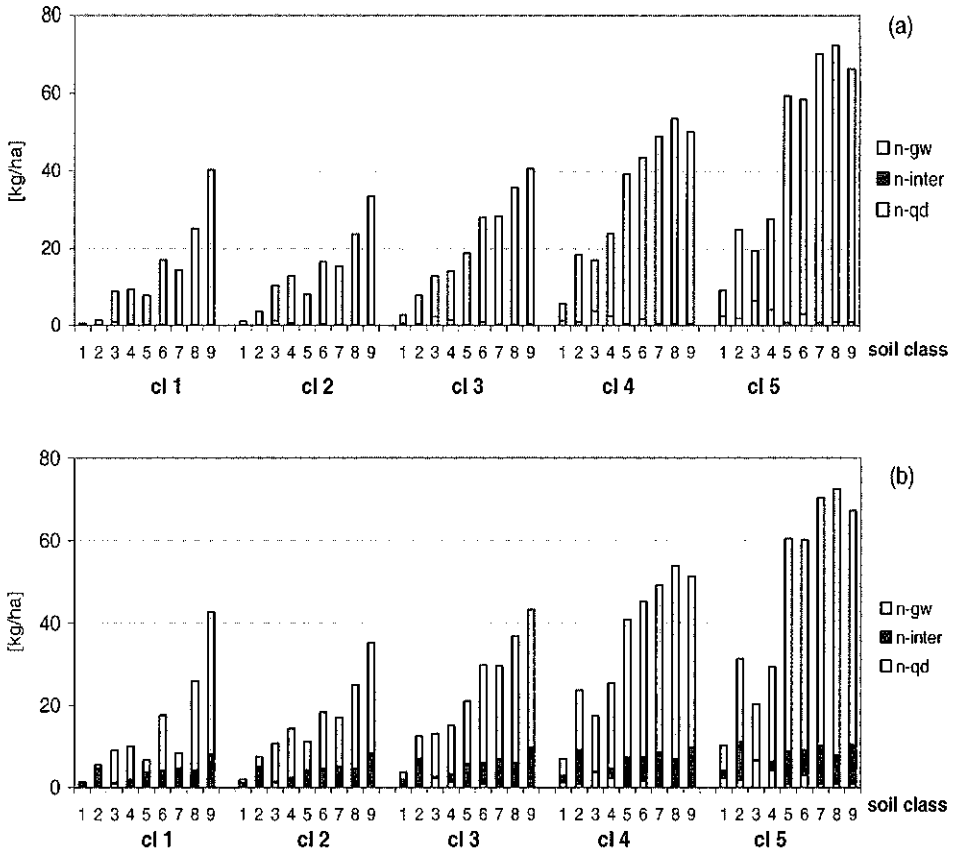


Fig. 1 Combined effects of climate (*cl1*, ..., *cl5*), soils (1, ..., 9), and elevation (*a* – $SS = 0.002$, *b* – $SS = 0.10$, where SS is the topographic slope) on modelled long-term average annual N losses, considering fluxes in direct runoff (*n-qd*), interflow (*n-inter*), and groundwater recharge (*n-gw*).

Figure 2 shows N fluxes: N mineralization, N uptake by plants, N denitrification, and N losses with water (or potential N leaching to groundwater, indicated as *leach+* in Fig. 2) for nine soil classes, considering the basic rotation and fertilization schemes. The modelling results for five climate zones were averaged for this example to exclude the climate effects. In soil classes 1 to 4, gaseous N losses are high, and leaching to groundwater is low. This pattern is attributed to a high field capacity and low saturated hydraulic conductivity, which enhances denitrification and assures their low permeability to water and associated fluxes. In contrast, leaching to groundwater is much higher in soil classes 7–9, while denitrification is zero in these soils. This is due to the larger proportion of sand and higher saturated hydraulic conductivity of these soils.

The effect of land use and land management represented by rotation and fertilization schemes, on N uptake by plants, denitrification, and N potential leaching to groundwater, is shown in Fig. 3 for four soils classes: 2, 3, 5 and 9. The effect of higher fertilization rates is obvious: all losses and uptake are higher when fertilization scheme 2 is applied. Also, changing the crop rotation affects N plant uptake and N losses; both are highest for rotation scheme 2, and lowest for rotation scheme 3.

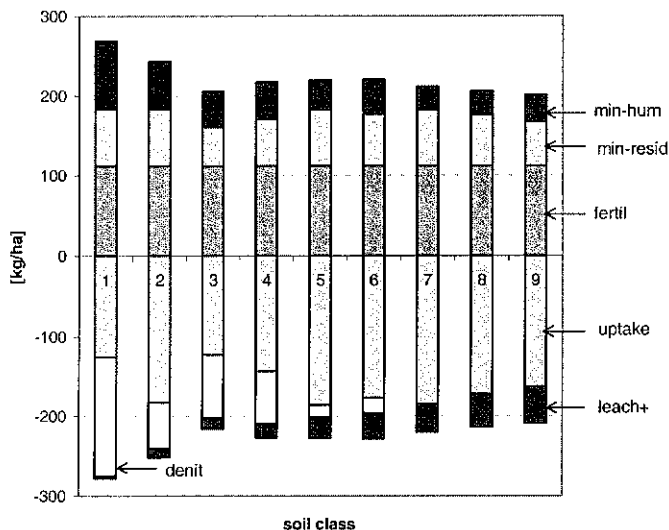


Fig. 2 Simulated long-term average annual $\text{NO}_3\text{-N}$ fluxes in nine soil classes for the basic rotation and fertilization schemes: fertilization by mineral N (*fertil*), mineralization of humus (*min-hum*) and from residues (*min-res*), plant uptake of N (*uptake*), N losses with water (*leach+*), and N denitrification (*denit*). The last three fluxes are depicted as negative values.

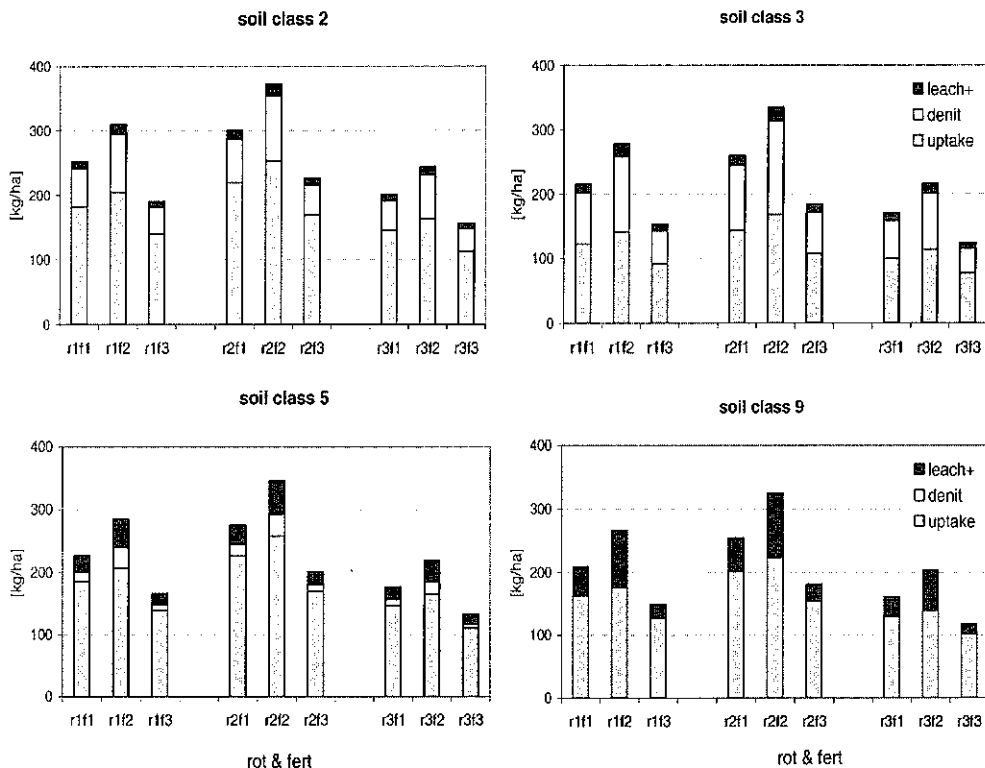


Fig. 3 Effect of rotation and fertilization schemes (*r1f1*, ..., *r3f3*) on simulated long-term average annual N fluxes: N uptake by plants (*uptake*), gaseous losses (*denit*), and N losses with water (*leach+*).

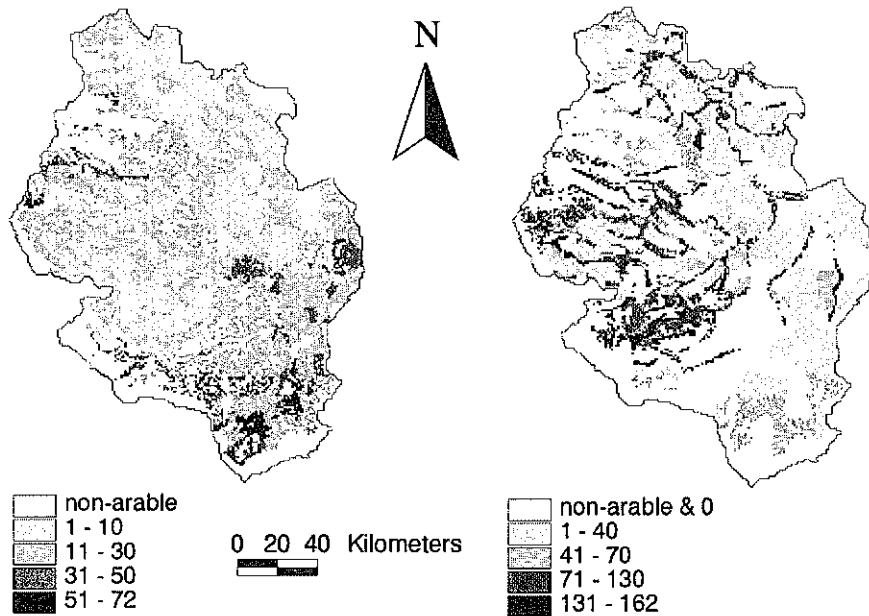


Fig. 4 Spatial distribution of the simulated potential long-term average annual N leaching to groundwater (left), and denitrification (right), in the Saale River basin for the basic rotation and fertilization schemes.

Modelling results for the potential average annual N leaching and denitrification for the basic rotation and fertilization schemes are mapped for the Saale River basin on a 1×1 km raster grid (Fig. 4). The same differences between soil types as shown in Figs 1 and 2, and the climate gradient from north to south are visible. Annual N leaching ranges from $1\text{--}15 \text{ kg ha}^{-1}$ in heavy loess soils (classes 1–5) in climate zones 1–3, to $50\text{--}72 \text{ kg ha}^{-1}$ in sandy soils (classes 7–9) in climate zones 4 and 5. In contrast, the highest denitrification (up to $160 \text{ kg ha}^{-1} \text{ year}^{-1}$) occurs on the floodplain close to river courses (soil class 1, which has the lowest leaching). The high denitrification is associated with the high field capacity and low saturated hydraulic conductivity, which may lead to the oxygen deficit conditions.

An indirect validation of the N balance for the Saale River basin was performed using regional data on the N balance components for northern and central Germany, according to the so-called robust approach (Krysanova & Becker, 1999). Regional data on N dynamics in soil and N fluxes for northern Germany were collected from the literature (Bodennutzung, 1985; Scheffer *et al.*, 1984; and others) to obtain region-specific ranges for the validation of the simulated N balance. The modelling results presented in Fig. 4 are comparable to the ranges, and the differences between sub-regions are plausible.

Finally, the assessment of sensitivity of the modelled potential N leaching to variations in natural and anthropogenic conditions was done using the full set of simulated long-term average values. The average N leaching for the specific case was related to the global average N leaching. The variation between different soil classes is the highest of that for any other parameter (Fig. 5) and is more than one order of magnitude between classes 1 and 9. Secondly, climate conditions and fertilization

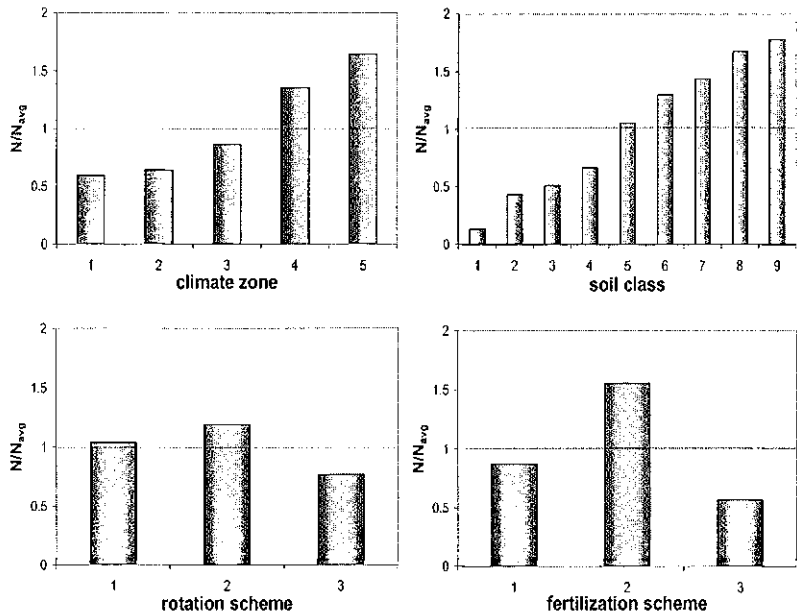


Fig. 5 Sensitivity of the simulated potential N leaching to groundwater, to climate, soil type, rotation, and fertilization, estimated as the ratio between the average N leaching for specific cases and the global average N leaching.

schemes produce the next largest variations $\pm 65\%$. The sensitivity to crop rotations is the smallest $\pm 20\text{--}25\%$. The relative importance of natural and anthropogenic factors affecting N leaching in the Saale River basin is as follows: (1) soil, (2) climate, (3) fertilization rate, and (4) crop rotation. The simulation experiments provide a basis for the fuzzy-rule based metamodel approach, which is described in Haberlandt *et al.* (2001).

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