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N-dynamics and nitrate leaching under rotational and continuous set-aside—a case study at the field and catchment scale

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Abstract

Set-aside comprising rotational (Rot_fal) or continuous green fallow (Cont_fal) and recultivated in autumn or spring was assessed using models at different spatial scales (field, catchment). Nitrogen (N) dynamics and nitrate leaching in sandy arable soils were simulated using digitized maps of soil properties, land use distribution and crop management for a 6-yr period. The rotational and Cont_fal scenarios took 17 to 22% of the arable land out of production, relative to a nonfallow (Non_fal) scenario, with the removals randomly distributed over the catchment. The scenarios provided information on the relative importance of set-aside for hydrology, nitrogen loss and conservation. The sample simulations for the Non_fal crop rotation at the field scale agreed with measurements for comparable sites. The Cont_fal decreased drainage more than the rot_fal (32 vs. 14%) relative to the nonfallow (Non_fal) scenario. At the field scale, Cont_fal met the EC-standard for nitrate in drinking water giving a concentration of 48 mg l^{-1}, but under Rot_fal, nitrate concentration was very similar to Non_nfal conditions ($\sim$130 mg l^{-1}) because of simultaneous drainage reduction. At the catchment scale, the mean of nitrate concentration for the Cont_fal sites was only half of that for the Rot_fal and spring tillage reduced nitrate concentrations by another 50% relative to autumn tillage. For the total catchment, however, the contribution of Rot_fal and Cont_fal to the total nitrate load were similar because more area was involved in the Rot_fal treatment. N accumulation and mineralization after Cont_fal exceeded the N demand of subsequent crops. Con_fal may therefore lead to groundwater pollution because mineralizable N was positively related to nitrate leaching at the catchment scale. The sensitivity of set-aside parameters for the simulation results was analyzed. © 1998 Elsevier Science B.V.

Keywords: Land use; Crop rotation; Green fallow; N turnover; Nitrate leaching; Modelling; Sensitivity analysis; Spatial variability

1. Introduction

Various management practices are allowed by EC regulations on set-aside arable land and its reintegration into crop rotations (EC, 1992). Generally, one can distinguish rotational fallow (Rot_fal) and continuous fallow (Cont_fal) which both are linked to a nonexport rule for products during one or 5 yr, respectively. This change in land use raises ecological questions about the fate of nutrients that accumulate in the soil and may be of economic value. In Germany, about 900,000 ha of arable land were set aside in 1990, of which more than two thirds were Cont_fal (5 yr) and may now be taken back into crop production. The cultivation of long-term leys (John-

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ston et al., 1994) and the ploughing of grassland (Richter et al., 1989; Richter and Beblik, 1996) cause substantial mineralization of nitrogen (N) and leaching of nitrate because of previously accumulated N. For Rot_fal, Kersebaum et al. (1993) showed that N mineralization after early ploughing and the low uptake rate by succeeding crops caused nitrate losses.

Some fundamental differences in N turnover processes exist between rotational and long-term green fallow because of age and soil biological activity. The N turnover rate under Rot_fal may be hypothesized to be like that under an ordinary crop or green manure, and that under continuous green fallow may be as low as that under grassland (Jenkinson, 1990). The induced or natural succession of leguminous plants because of N depletion will increase the amount of potentially mineralizable N which in turn makes a fast growing 'catch' crop mandatory after ploughing in autumn (Heß and Franken, 1988). Furthermore, the composition of residues incorporated in the soil may change the net mineralization rate. Buhse et al. (1993) found initial turnover rates after ploughing 3 yr old grass clover ley were less than when sugar beet leaves were incorporated. Nevertheless, 6 yr of ley caused considerable N enrichment and risk of loss (Johnston et al., 1994).

N dynamics are also determined by soil properties. These may vary at all scales. To assess these overall effects, set-aside management practices have to be evaluated under various ecological conditions which include the position of set-aside within the rotation. Simulation models for carbon and N turnover processes in the plant–soil system have been adopted for many scales and purposes. The N dynamics model, validated for various agricultural soils and crops (Kersebaum and Richter, 1991; Kersebaum, 1995; Richter et al., 1996; Richter and Beblik, 1996), will be extrapolated to the environmental impact study described below. The overall objective of this work is to quantify the effects of set-aside management on nitrate leaching to the groundwater and the accumulation of mineralizable N in the soil. In particular, the simulation study was made to evaluate the influence of the following factors on nitrate concentration in the drainage and soil fertility: (i) set-aside type: rotational vs. continuous green fallow; (ii) management practice: ploughing in autumn vs. ploughing in spring; (iii) spatially variable soil data on the catchment scale.

2. Materials and methods

2.1. Soils in the catchment

The simulation study was made for the Eisenbach catchment, located in the north German pleistocene sand plain (Illinoian), approximately 65 km north of Braunschweig (Lower Saxony). The catchment is between 60 and 130 m above sea level. This region is characterized by sandy soils (sand to loamy sand and sandy loam), classified as Humic Podzols or as a subtype of Luvisol, which have developed on wind blown pleistocene and holocene sediments of variable depth and clay content. In the northern part of the catchment, soil development was influenced by the presence of a terminal moraine (Warthe). The organic matter content in the A horizon, therefore, varies widely (ranging from <1 to $>15\%$). Soils with lower field capacity (<20 vol.%) are predomi-

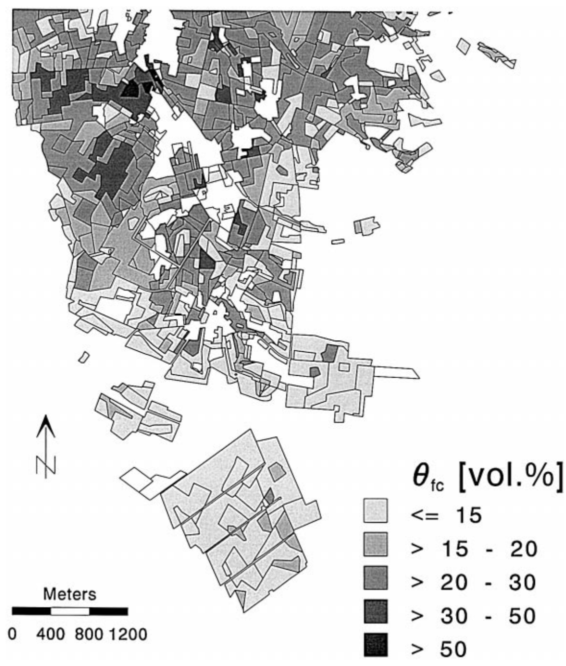

Fig. 1. Mean field capacity of soils, θ_{fc}, in the profile (0–90 cm) for the catchment area.

nant in the southern part of the catchment. In the central and northern part, the field capacity reaches 30 vol.% with increasing clay, silt and organic matter content (Fig. 1). Most soils are well drained (> 1.3 m below surface) and the maximum rooting depth in these sandy soils is considered to be 0.7 m (AG Bodenkunde, 1982). The soil data are recorded according to local stratification and are available for the 'Eisenbach' catchment on digital maps (1:5000), with an accuracy of 0.1 m depth increments. Detailed data sets of an experimental site, typical for this catchment, have been published elsewhere (McVoy et al., 1995).

2.2. Land use and management

Data on land use properties such as crop rotation are available for about 500 ha on digital maps of the catchment between 1987 and 1991 (e.g., Fig. 2). In total, about 21 different rotations of 11 crops were found, but about 87% of the total arable area was used for winter and summer barley, winter rye as well as sugar beets and potatoes. When grouped according to the main sowing period (autumn vs. spring) the distribution of crops showed considerable temporal variation. The portion of spring-sown crops like grain (barley and oats) and row crops (potato, sugar beets and corn) ranged from 50 to 70% of the total area (Fig. 3). Cover crops were of no significance despite the wide-spread winter fallow. Continuous records of yields, amounts of fertilizer applied, residue incorporation and mineral N in the profile after harvest (residual N_{min}) were evaluated to create mean crop specific management profiles (Table 1), with sowing and harvesting dates. Mineral fertilizer N was applied at annual rates of 145 to 200 kg N ha^{-1} for winter grains and up to 124 kg N ha^{-1} for spring grains during the main growing season (March–June) in three and two splittings, respectively. Of row crops, sugar beets received up to 200 kg N ha^{-1} and potatoes about 135 kg N ha^{-1}. Additionally, on less than 20% of the total area, between 50 and 160 kg N ha^{-1} were added by organic fertilizers during the preceding autumn. The N balance, calculated from the difference between N

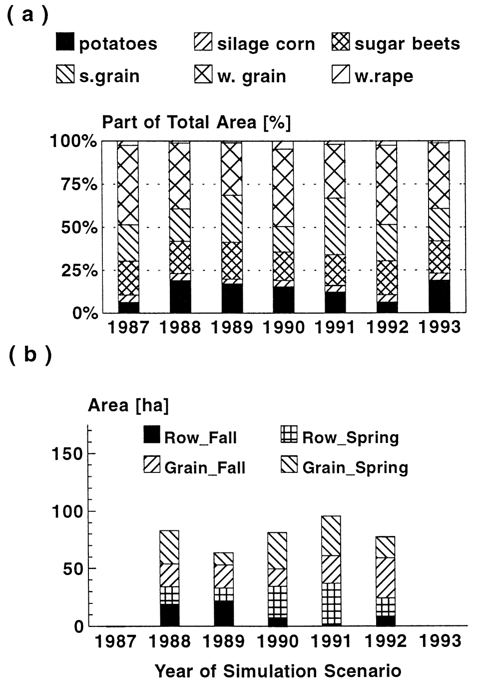

Fig. 3. (a) Temporal change of the relative distribution of crops across the 508 ha of the 'Eisenbach' catchment and (b) the proportion of fallow initiation (grain or row) and reintegration (autumn or spring), respectively.

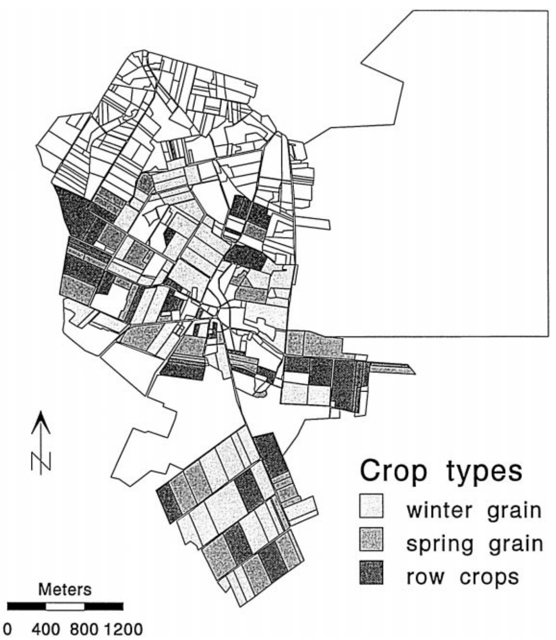

Fig. 2. Distribution of general crop types in the 'Eisenbach' catchment, 1987.

Table 1
Characteristic management profiles for important crops in the ‘Eisenbach’ catchment

Crop (% arable land)	Sown (day/month)	Harvest[a] (day/month)	Yield and residue composition			N-fertilizer	N-balance[b] (kg N ha^{-1})	
			dt ha^{-1}	HI[c]	N_r(%)	Min./org.	Min.	Min.+org.
Winter barley (10)	20/9	27/7	50	0.5	100	195/ –	97	–
Winter rye (12)	15/10	7/8	45	0.42	100	195/ –	121	–
Summer barley (25)	21/3	18/8	46	0.53	100	124/ –	37	–
Sugar beets (20)	21/4	15/9	450	0.55	50	208/50	116	180
Potato (21)	21/3	15/9	360	0.71	90	135/160	−5	125

[a] Harvest and residue incorporation.
[b] Fertilizer-N minus N export with the harvest products according to Kleeberg et al. (1993).
[c] Harvest index = product/total dry matter production.

applied and N removed in the products, showed an annual surplus, ranging from −5 kg N ha^{-1} on sites fertilized with mineral N exclusively to +180 kg N ha^{-1} on fields which also received manure or slurry (Table 1).

2.3. Modelling procedure

2.3.1. Description of the N dynamics model

The N dynamics model MINERVA was used mainly as described by Kersebaum and Richter (1991). It has lately been validated for various arable systems (Kersebaum, 1995; Richter et al., 1996, 1997). The model consists of three submodels: (1) water balance and water flux; (2) N mineralization and nitrate transport; (3) plant growth and N uptake. The extended model considered here will be briefly described in its modifications including the submodels for nitrification, plant growth as well as its coupling to Geographic Information Systems (GIS) as documented elsewhere (Richter and Beblik, 1996).

(1) The water balance is calculated from precipitation and potential evapotranspiration (PET) using a simple empirical method based on daily vapour pressure deficit (Haude, 1955) and monthly crop-specific coefficients (Heger, 1978). The potential evaporation is a function of leaf area index (Goudriaan, 1982) and reduces to its actual value according to the relative water content in the soil profile (van Keulen, 1975). Water uptake by plants is distributed over depth relating the flux to the root length density and plant available water in the profile (Groot, 1987). Water flow (drainage) is simulated 1D-vertically only, and occurs from one layer to another when the water content of the respective soil layer exceeds field capacity, θ_{fc}. Upward flux from a mostly deep groundwater table and capillary rise are ignored. All the capacity parameters required, such as field capacity, θ_{fc}, and residual water content, θ_{wp} (wilting point), are available for the model from tables relating empirical values to texture classes, organic matter and hydromorphic properties (AG Bodenkunde, 1982). For this purpose the profile is subdivided into 0.1-m increments.

(2) N mineralization is described by two simultaneous temperature and water dependent first order decay functions for separate N pools, decomposable (N_d) and recalcitrant N (N_r). The latter pool is derived from a fraction of total soil organic matter content (0.13) in the top horizon (0.2–0.3 m), using a general C:N-ratio of 17 (McVoy et al., 1995). Both pools are regenerated by residue and organic fertilizer addition determined by recorded yields, listed residue–harvest ratios (harvest index) and partitioning into separate pools of mineralizable N (Table 1). In the original modelling approach, the nitrification process is assumed to occur instantaneously after ammonification (Kersebaum and Richter, 1991). In the extended version, nitrification is simulated explicitly depending on the temperature, pH and water content of the soil using a submodel following the concept of Hagin et al. (1984). Nitrate transport with the drainage is simulated as a 1D-vertical convective–dispersive process using the calculated water contents and fluxes. The dispersion coefficient is the sum of diffusion related to texture dependent tortuosity and hydrodynamic dispersion (Kersebaum, 1995). The processes of atmospheric N deposition as well

as denitrification are ignored in this modelling exercise. Ammonia volatilization after slurry application is approximated by a simple exponential function describing gaseous N loss as a function of time between spreading and incorporation into the soil.

(3) The simulation of crop growth and development is based on the SUCROS model (van Keulen et al., 1982). The model has been modified and calibrated for winter wheat to describe dry matter production also as a function of critical and optimum N content in the plant (Kersebaum and Richter, 1991). Photosynthesis accounts for a decreasing light extinction in the canopy (Goudriaan, 1982), plant phenology is based on temperature sum (Weir et al., 1984) and the root distribution is approximated as described by Whitmore and Addiscott (1987). N uptake is determined by the demand derived from dry matter and the optimum N content depending on the plant development stage. It is limited by the N content of the soil and to a maximum uptake rate of 6 kg N/(ha d). Parameters for all major crops (van Heemst, 1988; Richter and Beblik, 1996) are included, some of which may have a preliminary character because of ongoing field testing. For the same reason, the simulation approach for set-aside is simplified. Assuming the behaviour of a cover crop without N export, its growth and N uptake is described by a simple function based on the temperature sum. It is also assumed that rooting depth increases at a rate of 0.1 m per 100°C days (base temperature of 4°C) and N uptake is also limited to a maximum rate of 6 kg N/(ha d).

2.3.2. Modelling assumptions for the set-aside scenarios

For the Non_fal scenario the recorded land use (1987–1991) was extended until 1993, according to its crop rotation, thus meeting the condition of equal simulation periods for all scenarios. The minimum requirement was based on 5 yr of Cont_fal plus previous and succeeding crops. Fig. 3a shows the change in relative distribution of the major crops over the years. Despite the varying weather conditions, which can influence maturity, harvest time and yield, N efficiency and residual nitrate, the scenarios were simulated with the standard data sets for the crop management (Table 1). For initial conditions, the residual N_{min} was assumed to be equal to the average mineral N contents in the profile measured at harvest; these ranged between 44 and 100 kg N ha^{-1} (Table 2).

Table 2
Mean crop specific mineral N content in the profile (0–0.9 m) after harvest

Previous crop	Sampling	Mineral N content (kg N ha^{-1})			
		−0.3 m	−0.6 m	−0.9 m	0–0.9 m
Winter barley	September	54	12	5	71
Winter rye, triticale	August	26	30	7	63
Winter wheat	September	56	18	4	78
Winter rape	August	79	12	9	100
Summer barley	September	20	13	1	44
Sugar beets	November	28	7	11	46
Potato	September	38	12	12	62
Silage corn	October	45	30	20	95

For set-aside scenarios a fast-growing cover crop was chosen and assumed to be cut in the summer (July 15th). It was intended to account equally for all combinations of set-aside initiation (summer or autumn after grain and row crops, respectively) and its reintegration into the rotation (ploughing in autumn or spring before winter and spring crops, respectively). In case of Rot_fal the set-aside portion varied between 14 and 21% of the total area because of the variable field size. Slightly more Rot_fal was sown in summer and ploughed in spring because of extensive growing of grain and spring crops (Fig. 3b). At ploughing, the green fallow residues were incorporated to a depth of 20 cm and the fraction of easily mineralizable N in the residues was assumed to be 50% (Nordmeyer and Richter, 1985).

Cont_fal was placed in the rotation mostly after grain, less often after row crops because of their late harvest. Almost as much Cont_fal was ploughed in autumn as in the spring (46 and 58 ha, respectively). The N accumulation and turnover of the system was characterized as follows. The summer cut remained as litter on the surface and the aged plant material of long-term fallow was made less susceptible to mineralization by allocating 5% of the residue N to the easily mineralizable pool (N_d). The N turnover rate in the no tillage system was assumed to be reduced by 50% (Jenkinson, 1990). The natural occurrence of leguminous plants in N deficient systems was not

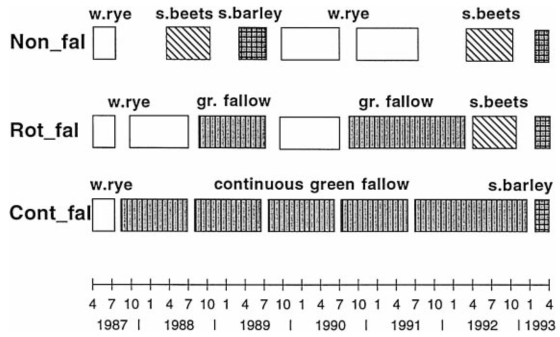

Fig. 4. Diagram for field scenario simulation of nonfallow (Non_fal), rotational fallow (Rot_fal) and continous fallow (Cont_fal).

explicitly considered because of the spatial and temporal variability of the process. N accumulation in the set-aside, however, was accounted for by N addition to the system at a rate of approximately 55 kg N ha^{-1} annually. Firstly, a continuous N addition by wet deposition amounted to approximately 30 kg N ha^{-1} (based on annual 600 l m^{-2} precipitation) and, secondly, another 25 kg ha^{-1} flush of mineral N (N_{min}) at times of mid-summer maintenance (cutting) was assumed for the green fallow fields. These simple assumptions were chosen to mimic the enhanced immobilization of N in the plant material which in reality may also result from N_2-fixation by propagation of leguminous plants.

2.3.3. Simulation procedure

For the field simulations a standard sample of the rotation and its changes in the set-aside scenarios were selected from the total data set to check for the plausibility of the results. Fig. 4 indicates schematically how the cropping sequence related to sample results shown in Fig. 6. The sample simulation of Rot_fal, considered both types of reintegration into the crop production (autumn, spring).

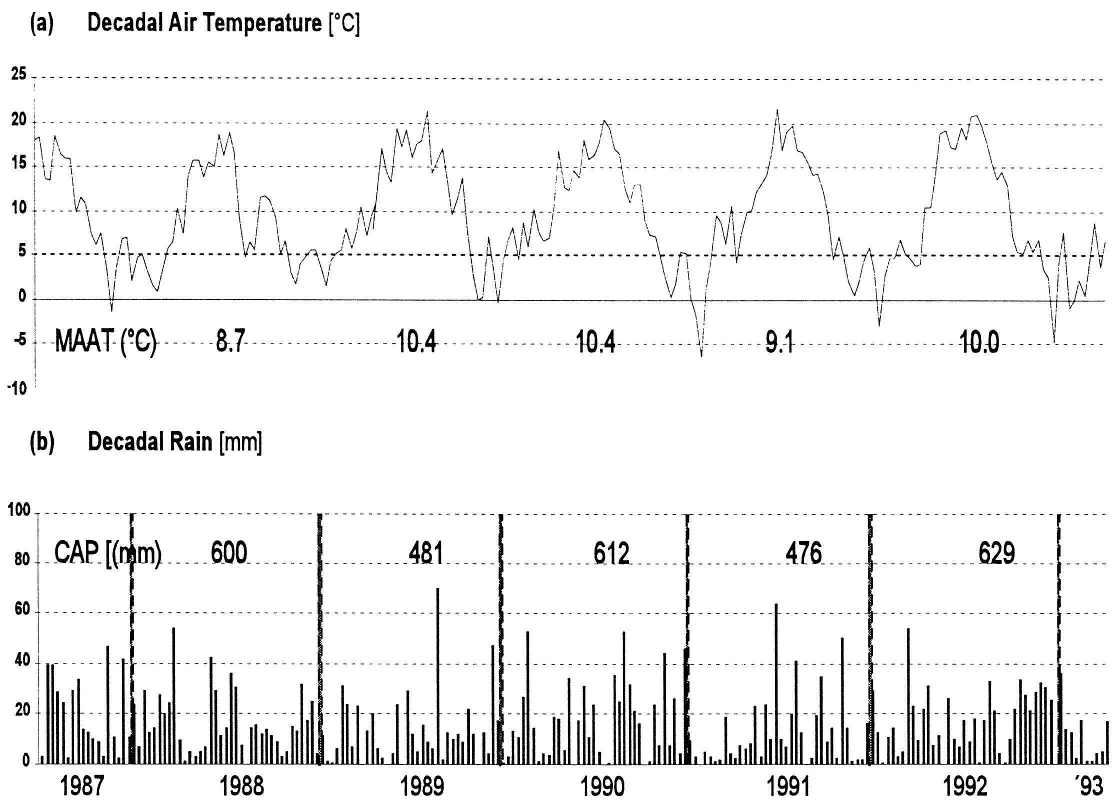

Fig. 5. Course of aggregated daily weather data during the simulation: decadal means of daily mean air temperature and decadal sums of precipitation; mean annual air temperature (MAAT, °C) and cumulative annual precipitation (CAP, mm).

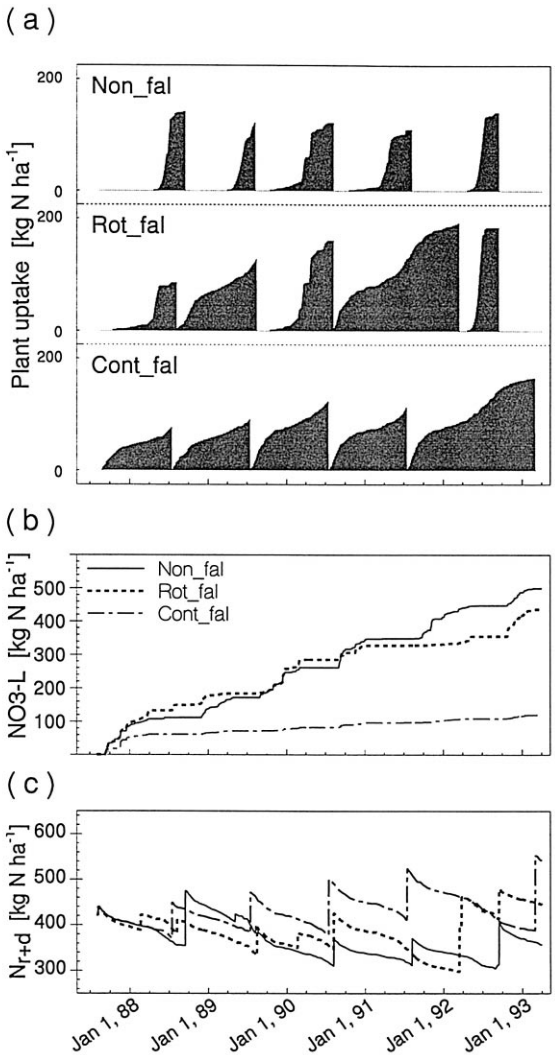

Fig. 6. N-dynamics of field scenario simulations (Non_fal, Rot_fal, Cont_fal). (a) N uptake pattern; (b) nitrate leaching loss; (c) potentially mineralizable N.

For the simulation at the catchment scale, the pedological and agronomical site properties were coupled via data created by ARC/INFO for site description files, containing 481 different soil profiles and 146 cropping sequences. After intersection of soil and land use coverages all patches smaller than 200 m^2 were considered to be artefacts and consequently neglected. The ecotope size was log-normally distributed with a mean of 1.1 and a mode of 0.6 ha. Each scenario was represented by simulations for 461 combinations of soil–crop rotation with a daily time step from post-harvest 1987 to spring 1993. Weather data from a nearby weather station were used showing a very wet and cool winter in 1987 followed by warmer and drier winter periods (Fig. 5). In this period, the total precipitation was about 3200 mm.

2.4. Statistical methods

Descriptive statistics were conducted on the original data sets of the simulation output. Outliers had been eliminated previously, following the method described in the work of Sachs (1978), p. 219. The mean and distribution of nitrate fluxes entering the groundwater were calculated using values transformed according to the weight of ecotope size and the amount of drainage.

2.5. Sensitivity analysis for modelling set-aside

The variability of two parameters of the set-aside is relevant with respect to the management related environmental impact. The susceptibility of the incorporated residues and organic N to mineralization, and, secondly, the size of the mineral N flush, which is assumed to be associated with maintenance (cutting) during set-aside and ploughing afterwards. Both may vary with the quality of the set-aside plant material. The N partitioning in the set-aside residues (originally 50% in N_d and N_r) is changed stepwise in the range of 25 to 95% N_r for the first set of simulations in the sensitivity analysis. This corresponds to a relative change of −50 to +90% of the standard. Table 3 shows that for the second set of

Table 3
Modelling assumptions for the sensitivity analysis of changing N_{min} flush during (maintenance) and after set-aside (ploughing)

Profile (cm)	Rate of change % (kg N_{min} ha^{-1} layer^{-1})					
	Maintenance		Ploughing			
	0	−33	+25	0	−25	−56
0–30	15	15	35	25	15	10
30–60	10	2.5	10	10	10	5
60–90	5	2.5	5	5	5	2.5
0–90	30	20	50	40	30	17.5

simulations in the sensitivity analysis the N_{min} flush corresponds to a relative change of +25 to − 56%.

3. Results and discussion

3.1. Field scale simulations

The principal results of simulating the N dynamics at the field scale are visualized for a typical 4-yr crop rotation (Non_fal) and for the introduction of the two different green fallow types (Fig. 6). The selected crop rotation starts with sugar beets (1988) after winter rye and is followed by summer grain (1989) and winter rye (1990, 1991). The N uptake patterns of these different crops reflect reality closely (Fig. 6a). In the simulation, both grain crops reach maturity and the simulated partitioning of harvest- and residue-N is in good agreement with the recorded N balance. Depending on the annual dry matter production 70–85 kg N ha^{-1} are simulated to leave the system with the winter rye harvest, straw remaining at the field. The recorded N balance of +121 kg N ha^{-1} (Table 1; Kleeberg et al., 1993) is met well by the simulation: 85 kg N ha^{-1} are simulated to enter the pool of mineralizable N, and the mineral N present in the soil at harvest (Table 2) differs from that in spring by about 40 kg N ha^{-1}. For summer barley, the simulated pool addition (32 kg N ha^{-1}) agrees with the recorded N balance of 37 kg N ha^{-1}. The greatest difference occurs for sugar beets because of the small export with the harvest (max. 50 kg N ha^{-1}). However, the simulated N pool addition of 140 kg N ha^{-1} is also within the range of the observed N balance (116 to 180 kg N ha^{-1}). With respect to the environmental impact, the simulation of the N dynamics can be considered sufficiently realistic, although, further conceptual changes need to be made to the parameter set for sugar beet growth as Kersebaum (1995) found. Finally, the simulated course of nitrate–N leaching for the Non_fal scenario at this particular field site (Fig. 6b) shows a stepwise increase of N losses during 6 subsequent winters between 110 and 80 kg N ha^{-1} annually, amounting to 500 kg N ha^{-1} in total (Table 4). During the same period mineralizable N decreases by approximately 100 kg N ha^{-1} within the simulation (Fig. 6c; Table 4).

The second example, simulating Rot_fal, includes two periods of set-aside, which differ in their effectiveness in reducing nitrate leaching and increasing soil fertility: The N leaching loss under Rot_fal is very high when ploughing occurs in autumn 1989 and is similar to that under the Non_fal rotation. When ploughing occurs in spring 1992, there is about 100 kg N ha^{-1} less nitrate leaching because of the Rot_fal which started in summer 1990 and was maintained until 1992 (Fig. 6b). The larger N uptake of succeeding crops, to be seen with winter rye in 1990 and sugar beets in 1992, is a phenomenon frequently observed with Rot_fal in practice. Furthermore, the overall benefit of the green fallow can also be seen in maintaining the mineralizable N pools, $N_{r,d}$ (Fig. 6c; Table 4).

The third example, Cont_fal, reflects ‘optimum’-management, with sowing in the summer after grain harvest and spring-ploughing. The N uptake of the cover crops reaches 50 to 80 kg N ha^{-1} before winter and keeps increasing afterwards with a frost resistant species. In the following years, N uptake increases and reached a maximum of more than 150 kg N ha^{-1} in spring 1993 before ploughing. Under these conditions the nitrate leaching loss is greatly reduced (Table 4). N uptake and leaching compete, so extremely wet and cold weather resulted in about 50% of the total nitrate loss occurring in the first winter (1987–1988). The total loss of about 120 kg N ha^{-1} produced a mean nitrate concentration of

Table 4
Simulated cumulative drainage (D) and nitrate loss (NO_3-L), mean nitrate concentration (NO_3-C) and change in potentially mineralizable nitrogen ($\Delta N_{r,d}$); 5 2/3-yr scenarios

Set-aside type	D (mm)	NO_3-L (kg N ha^{-1})	NO_3-C (mg l^{-1})	$\Delta N_{r,d}$ (kg N ha^{-1})
Nonfallow (Non_Fal)	1659	500	133	−99
Rotational fallow (Rot_Fal)	1430	436	135	+23
Continuous fallow (Cont_Fal)	1125	121	48	+120

less than 50 mg l^{-1} thus meeting the EC-standard for drinking water. This compares well with the Rot_fal, where a simultaneous decrease of nitrate loss and drainage occurred without any major change in nitrate concentration (Table 4). Both types of intensively managed green fallow definitely reduce groundwater recharge which may alter with a less intensive type of cover crop (Magid et al., 1994). Both factors, water quantity and quality, need to be considered in land use planning. The other ecological effect is the change in the pool of mineralizable N, which influences the sustainability of the ecosystem. The Cont_fal left 200 kg N ha^{-1} more mineralizable N than the Non_fal system (Fig. 6c; Table 4). The reuse of this N, part of which is easily decomposable (N_d) and a potential resource for the next crop, will be lost when the soil is ploughed too early in the autumn. Leaching is related to texture and field capacity, so the effects shown here for sandy soils will be less marked in loam soils. Likewise, the residue partitioning of grassland is related to texture (Hassink, 1994) and, more generally, turnover rates are lower in soils with high clay contents (Jenkinson, 1990).

3.2. Catchment scale simulations

3.2.1. Spatial variability within the catchment: non-fallow scenario

For all important processes and parameters, a wide spread set of values is obtained simulating the Non_fal scenario (Table 5). Less than 0.8 ha (0.15%) are considered outliers and eliminated before calculating the descriptive statistics. The coefficient of variation for N mineralization is larger (40%) than for drainage and nitrate leaching (20%). On the average, less than 50% of the overall precipitation (3200 mm) is drained at 0.9 m below surface corresponding to about 250 mm annually. Because of the variability in field capacity of the soil the 95% confidence limits of drainage range from 1010 to 1740 mm. For less than 2% of the total catchment area extremes at the lower or upper end of the normal distribution are simulated.

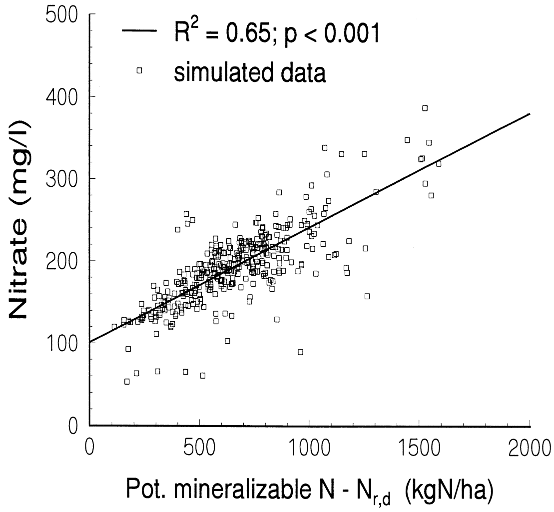

Fig. 7. Correlation between simulated potentially mineralizable N in the A_p-horizon (0–0.2/0.3 m) and simulated nitrate concentration in the drainage.

The simulation of the Non_fal N dynamics for all 461 soil–land use combinations results in a wide distribution of nitrate concentrations ranging from 50 to about 400 mg l^{-1}. This is largely due to varying soil properties, water use and N uptake patterns. Field capacity determines drainage and hence nitrate dilution, and organic matter, and mineralizable N content also influence the nitrate concentration in the drainage (Fig. 7). Under Non_fal cropping, the long-term average nitrate concentration is proportional to the N mineralization potential of the soil ($R^2 = 0.65,\ p < 0.001$). These nitrate concentrations

Table 5
Mean values and descriptive statistics of different variables and processes for the nonfallow scenario across the catchment and simulation period after outlier elimination

Variable	N_d (kg N ha^{-1})	Mineralized (kg N ha^{-1})	Nitrate loss (kg N ha^{-1})	Drainage (mm)	Nitrate concentration (mg l^{-1})
Mean	623	831	612	1471	189
± SD	253	324	144	310	45
Min.	111	35	34	172	53
Max.	1588	2122	907	1981	388

are elevated far beyond the EC-limit for drinking water. However, simulated mean values of nitrate concentration are similar to those measured in the same region under arable soils without manure or slurry (40 to 309 mg l^{-1}; Kleeberg et al., 1993). For another region with sandy soils, average nitrate concentrations ranging from 120 to 260 mg l^{-1} were measured in soil profiles deep below the root zone (0.9 to 10 m) and agreed very well with simulated concentrations for those sites where residual nitrate could be inferred for the crop rotation (Richter et al., 1997).

The amount of potentially mineralizable N varies with time and the type of crop residue, as shown above. This variation is increased by the variable distribution of soil organic matter which ranges over an order of magnitude at the catchment scale (Fig. 7). For grain crops the modelled residue partitioning has been confirmed by measured and recorded harvest indices. For sugar beets plant growth modelling and the results of harvest–residue partitioning are less reliable, as discussed for the field site. The general validity of these results is also restricted for potato crop growth simulation at the catchment scale and its N partitioning. During the whole course of the scenario the N added to the N pools (90% recalcitrant) ranges between 115 to 169 kg N ha^{-1}, which is close enough to the recorded balance (Table 1), also considering the precision of field measurements. However, simulated N exported in the potato harvest varies greatly with time ranging between 109 and 32 kg N ha^{-1} in 1988 and 1992, respectively.

3.2.2. Set-aside effects on the N dynamics

The results of both set-aside scenarios suggest a marked decline in the overall weighted mean nitrate concentration in the drainage (Table 6). Compared with the Non_fal scenario, set-aside reduces the average nitrate concentration by about 13%. A closer look into the interaction of management type (ploughing date) and N dynamics identified autumn recultivation as responsible for lowering the ecological efficiency: Autumn ploughing of set-aside causes a significant ($p < 0.05$; Scheffe-test) 50% increase in the nitrate concentration in the drainage relative to that ploughed in spring. This has been found in various experiments and a ban on it has been introduced into water protection regulations in drinking water catchments. The decision to plough in autumn depends heavily on the requirements of the crop rotation which ultimately depends on the market.

Table 6
Weighted mean of nitrate concentration in the cumulative drainage (mg l^{-1}) after 5 years of simulation (7/87 to 3/93) for landuse scenarios across the catchment and subsamples (date of recultivation)

Subsample	Fallow scenario (mg l^{-1})		
	Non	Rotational	Continuous
Catchment	189	169	164
Autumn ploughing	–	172	91
Spring ploughing	–	128	63

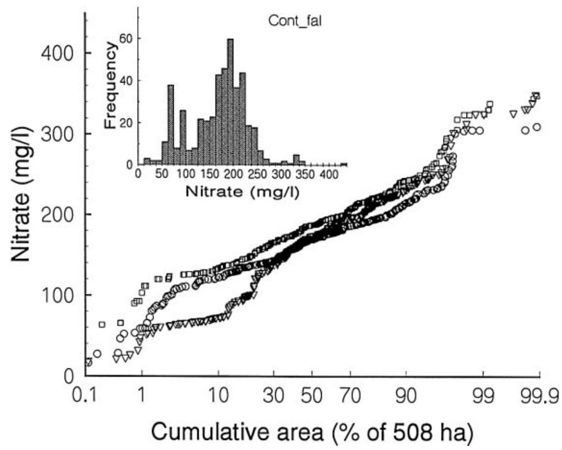

Fig. 8. Distribution of nitrate concentration in the drainage across the catchment (508 ha) after 5 2/3-yr of Rot_fal (○) and Cont_fal (▽) compared to Non_fal (□).

Looking at the nitrate concentrations at the end of each scenario (Fig. 8) the distribution shows a general shift to slightly lower nitrate concentrations for Rot_fal only. Under Cont_fal a bimodal distribution of nitrate concentrations occurs across the region, identifying the set-aside arable fields as a separate subgroup (Fig. 8-insert). This distribution also accounts for differences in management, like ploughing in autumn, which cause an increase of nitrate concentrations by 50% in sandy soils (Table 6). For crops like maize which take up N late in the season, losses may occur on such soils even after Cont_fal ploughed in spring. Johnston et al. (1994) observed net N loss of more than 100 kg N ha^{-1} for winter wheat following fallow and simulated a total leaching loss of 250 kg N ha^{-1} equivalent to a nitrate concentration of 400 mg l^{-1}. Therefore, the introduction of catch and cover crops seems mandatory for the ploughing of long term ley or green fallow. The effect of continuous set-aside at the catchment scale was characterized by a wide range of N accumulation (100 to 300 kg N ha^{-1}). Increased soil fertility may increase nitrate concentration, as the relationship between mineralizable N and nitrate concentration (Fig. 7) suggests.

Some aspects of the simulation study deserve further discussion: (1) the standardization of crop management profiles and initial conditions, and (2) simplification of some processes like plant growth and N uptake of certain crops, mineralization–immobilization turnover and nitrification. In reality, the variability of weather data will change crop maturity, yields and N use efficiency as well as N turnover in the soil. Therefore, mean values of harvest timing (Table 1) and mineral N at harvest (Table 2) for the whole simulation period will introduce errors into the 'real world' effects, as detailed studies in a 3 yr monitoring and validation period have shown: residual nitrate will increase in dry years (Richter et al., 1996), but not beyond the precision of field measurements, being approximately $\pm$20kg N ha^{-1} (Kersebaum and Richter, 1991). The initialization of mineral N according to long-term observations, on the other hand, may correct possible modelling errors like the poorly-described N uptake for crops that are not well parameterised. The phenomenon of differentiated N loss according to organic matter content is accounted for at the large scale spatial resolution, as shown here in the scenario simulations. Other publications also revealed increasing residual nitrate contents and losses with increasing organic matter content (Richter and Beblik, 1996).

In the context of nitrate leaching, the earlier assumption that mineralized N equals nitrate quantities (Kersebaum and Richter, 1991) was checked. In the season, the amount of ammonium in the soil is small, but at low temperatures nitrification will be inhibited. The nitrate leaching losses simulated with the earlier assumption were 6 to 8% higher than those with the explicit simulation of nitrification. The conserved N was suggested to remain in the profile as ammonium and to be taken up in spring. In case of ploughing green fallow in late autumn, however, this may be a considerable amount.

The simplification of green fallow modelling restricts the simulation results to a 'best case' scenario for N uptake efficiency. Further improvements must account for the diversity of plant species and their interaction with the soil–water system (Magid et al., 1994). Overall, the results of further possible green fallow treatments and crop rotations are in agreement with other simulations and measurements (Kersebaum et al., 1993): (1) late or spontaneous re-growth causes weak plant cover which results in higher nitrate losses to the environment, especially after row crops like corn or potato that leave large nitrate residues; (2) winter crops following ploughed green fallow do not take up enough N to reduce nitrate leaching. Oil-seed rape with an uptake of 30 to 60 kg N ha^{-1} may be the exception. Dry years can limit germination and reduce the development of the crop cover when no proper seed-bed has been prepared. Furthermore, in long-term fallow, the increase of N from symbiotic N_2-fixation may be temporally and spatially variable (Platte et al., 1995) and so influence the turnover rate before and after ploughing. Decreased turnover rates during the continuous green fallow have been accounted for by increasing the recalcitrant fraction of the residue-N during set-aside from 50 to 90%. This may be justified by considering the senescence of the residues and the lowered microbial activity attributed to the small water content of plant material left on the surface (Parton et al., 1987). At the end of the fallow, when the residues are incorporated and microbial activity is stimulated after ploughing, the simulation accounts for this change by assuming a larger fraction of easily mineralizable N. The mean annual immobilization of N, 50–60 kg N ha^{-1}, during green fallow in sandy soils seems a good approximation. Considering the higher turnover rates in sandy soils, it is in general agreement with the increase in the order of 80 to 100 kg N ha^{-1} annually found for loamy soils (Johnston et al., 1994; Jahn et al., 1994).

3.3. Model sensitivity for set-aside parameters

The importance of the above discussion on N turnover after set-aside is highlighted in the results of the following sensitivity analysis. The relative change of the weighted means is shown across the total catchment and the subsampled set-aside sites

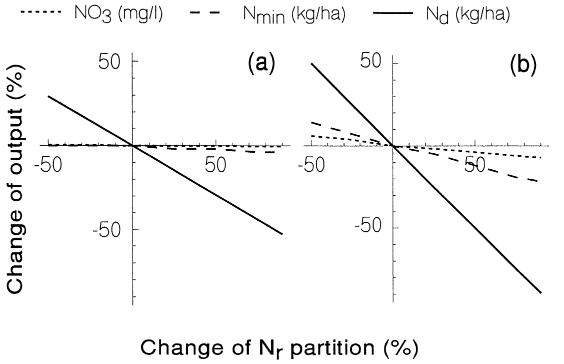

Fig. 9. Relative change of weighted means of the output at the end of the simulation: nitrate concentration in the percolate (NO_3), mineral N in the profile (N_{min}) and easily mineralizable nitrogen (N_d) averaged for the total catchment (a), and the set-aside ploughed in autumn (b), according to the change of N-partitioning in the set-aside residue (standard 50% recalcitrant nitrogen, N_r).

(Fig. 9). With increasing resistance of the plant residues incorporated, all ecologically relevant state variables decrease linearly. At the scale of the whole catchment, the effect is minimal (Fig. 9a): The mean nitrate concentration does not change visibly ($<1\%$), the change in N_{min} in spring is at most 5%. The reservoir of decomposable N, N_d, decreases proportionally with increasing resistance of the residues by about 50% (34 to 16 kg N ha^{-1}). For the subsample of autumn-ploughed set-aside, the nitrate in the drainage changes by up to +6 and −7% (Fig. 9b), being equivalent to 6 mg l^{-1} at most. On these sites, the N_{min} in the profile available to plants in spring may decrease by 20 kg N ha^{-1}, the easily decomposable N by 45 kg N ha^{-1}. When the sites are ploughed in early spring the effect of residue quality is only to be seen in the fraction of potentially mineralizable N, N_d, proportionally being reduced with increasing N_r-partition.

The sensitivity of the regionalized model to the changes of the N_{min} flushes is most relevant for the simulated nitrate leached. Reducing the annual mineral N flush during set-aside by 10 kg N ha^{-1} diminishes the amount of nitrate leached by about 40% of the total input reduction (−17 and −14 kg N ha^{-1}). The fractions of mineralizable N show a minor change only (−2 to −4 kg N ha^{-1}). The average nitrate concentration in the set-aside fields ploughed in autumn and spring diminishes by approximately 5 and 8%. At the catchment scale, this effect amounts to an overall change in mean nitrate concentration of −0.6%.

Changing the flush at ploughing from 40 kg N ha^{-1} in steps of ±10 kg N ha^{-1} results in a 1:1-decrease of nitrate leached from the fields recultivated in autumn. This is most plausible because the N uptake by most winter grains is rather limited as a result of slow development and shallow rooting. The model output for nitrate concentration is slightly nonlinear for the mean of the autumn subsample, and the relative change ranges between +5 and −7% (Fig. 10). At the catchment scale, the overall effect of changing the flush at ploughing is below 1%. For set-aside fields ploughed in autumn, the possible change of nitrate load because of the change in flush is smaller than 4%, relative to the total loss of 280 kg N ha^{-1}. The shift of ploughing date from autumn to spring has a tenfold larger effect. The simultaneous reduction of N_{min} flushes during and after set-aside (−10 and −22.5 kg N ha^{-1}) results in a reduction of the overall nitrate concentration by 1% at the catchment scale. Both autumn and spring ploughed set-aside sites are affected, with a reduction of nitrate concentration by −12 and −8%, respectively.

Overall, the sensitivity analysis for N turnover and nitrate leaching at the catchment scale shows that the effects of changing the parameters of set-

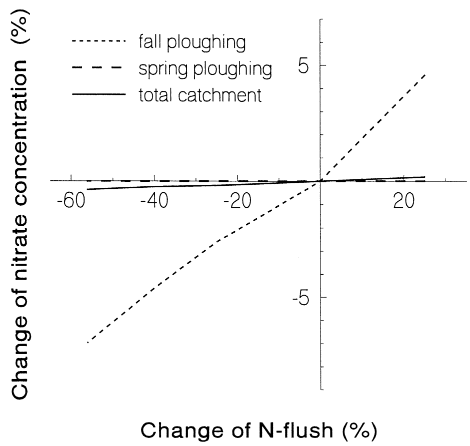

Fig. 10. Sensitivity of simulated nitrate concentration in different subsamples depending on the change of N_{min} flush after set-aside ploughing.

aside quality are a lot smaller than the effects of management change (ploughing) and spatially varying inputs.

4. Conclusions

From this case study on set-aside arable land, several conclusions can be drawn with respect to the interaction of management changes and environmental protection at different spatial scales. Beyond the original objective, insights are extended into the applicability of scenario simulations and their extrapolation.

Generally, the simulations of the crop rotations are largely based on validated parameter sets for grain crops representing about 70% of the area. The simulations show realistic N uptake patterns also for less well-known crops such as sugar beets or potatoes. Despite the simple modelling approach for green fallow, the simulations visualize a ‘feedback’ reaction of subsequent crops showing higher N uptake because of mineralization of accumulated residue-N. At the catchment scale, the application of the model reflects variable inputs in a coefficient of variation of 20 to 40% for drainage, nitrate loss and accumulation of mineralizable N. However, there is a variability at the catchment scale that has to be evaluated, so the parameter sets validated for some sites may not be transferable to other sites.

The question of optimum set-aside management is clearly answered from the results at the field scale: considering mean nitrate concentrations in the drainage at the end of the 5-yr fallow, continuous set-aside results in a 50% lower concentration compared with rotational green fallow. In both scenarios, spring ploughing saves another 50% of nitrate loss. At the catchment scale, however, both ‘treatments’ have a similar overall effect. In spite of the more efficient reduction of nitrate leaching, less fields are involved in continuous than in the annually rotating set-aside. This shows the importance of catchment studies averaging across treated and untreated area. The ecological effectiveness of long-term fallow, however, definitely has to include N accumulation. Cont_fal will increase N mineralization after ploughing, N uptake of subsequent crops, and also nitrate–N losses in drainage, especially when the soil is ploughed before winter. The rise of potentially mineralizable N after Cont_fal (100–300 kg N ha^{-1}) is a valuable resource, but should be considered as an additional potential hazard depending on the site properties, the management and the residue quality. The concepts of integrated agriculture could provide procedures that lead to a gradual decrease of these N sources. These might involve export of N in fodder crops. Further research is needed to determine how much N will be accumulated, released and profitably used under various types and intensities of set-aside for different soil texture classes.

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