Nutr Cycl Agroecosyst (2008) 82:299–314
DOI 10.1007/s10705-008-9192-0

RESEARCH ARTICLE

Evaluation of different agronomic strategies to reduce nitrate leaching after winter oilseed rape (*Brassica napus* L.) using a simulation model

J. Henke · U. Böttcher · D. Neukam · K. Sieling · H. Kage

Received: 15 November 2007 / Accepted: 14 July 2008 / Published online: 20 August 2008

Abstract Winter oilseed rape (OSR) demands high levels of N fertilizer, often exceeding 200 kg N ha^{-1}. Large amounts of residual soil mineral nitrogen (SMN) after harvest are regularly observed, and therefore N leaching during the percolation period over winter is increased. In this study agronomic strategies (fertilization level, crop rotation, tillage intensity) to control nitrate leaching after OSR were investigated by combining field measurements (soil mineral nitrogen, soil water content, crop N uptake) of a 2-year trial and another 5-year field trial with simulation modeling. The crop-soil model uses a daily time step and was built from existing and partly refined submodels for soil water dynamics, mineralization processes, and N uptake. It was used to reproduce the complex processes of the N dynamics and to calculate N concentration in the leachate and total volume of percolation water. Some parameters values were thereby newly identified based on the agreement between measured data and model results. Although SMN in the 60–90 cm layer was overestimated, the model could reproduce the measured data with an acceptable degree of accuracy. Overfertilization of OSR increased N leaching and therefore the precise calculation of N fertilizer doses is a first step towards prevent N leaching. Compared to ploughing, minimum tillage decreased N leaching when winter wheat was grown as the subsequent crop. Volunteer OSR and *Phacelia tanacetifolia* were grown as catch crops after OSR harvest. N leaching could be decreased especially when *Phacelia* was grown, but nitrate concentrations in the drainage water were higher and exceeded the European Union (EU) threshold for drinking water when volunteer OSR was grown. The results of this study provide strong evidence that reduced tillage or growing of noncruciferous catch crops decrease N leaching and may be used as an agricultural measure to prevent N pollution.

Keywords Catch crop · Modeling · Nitrogen leaching · Oilseed rape · Soil mineral N · Tillage · Winter wheat

J. Henke
Syngenta Seeds GmbH, Zum Knipkenbach 20, 32107 Bad Salzuflen, Germany

U. Böttcher · D. Neukam · K. Sieling · H. Kage (✉)
Institute of Crop Science and Plant Breeding, Christian-Albrechts-University, Hermann-Rodewald-Str. 9, 24118 Kiel, Germany
e-mail: kage@pflanzenbau.uni-kiel.de; hkage@t-online.de

Introduction

In Germany winter oilseed rape (OSR) has become an increasingly important crop in the last decades because of its profitability, beneficial value as a preceding crop for cereals, and the opportunity to grow OSR for biofuel production on set-aside land. OSR demands high levels of nitrogen (N) fertilizer, often exceeding 200 kg N ha^{-1}, to achieve maximum yields. However, N offtake by the seed is comparatively low, leading to high positive N surpluses on the crop scale (Shepherd and Sylvester-Bradley 1996; Sieling et al. 1999). In addition the N-harvest index of OSR, ranging between 0.6 and 0.7, is low compared with cereals (Malagoli et al. 2005). Although OSR residues lead to N immobilization after incorporation into the soil (Jensen et al. 1997; Justes et al. 1999; Trinsoutrot et al. 2000), soil mineral N (SMN) content increases regularly during autumn (Catt et al. 2000). As a consequence large amounts of nitrate are likely to be leached with drainage water (Sieling et al. 1999). Intensive tillage operations after harvest stimulate net mineralization of soil-borne N due to soil disturbance (Lickfett 1993). Additionally, the autumnal N uptake of winter wheat typically grown after OSR generally does not exceed 20–30 kg N ha^{-1} under the climatic conditions of NW Germany (Lickfett 1993; Sieling et al. 1999). However, there are several well-known agronomic measures to reduce mineralization of soil organic N and thereby nitrate leaching after harvest. Firstly, reducing tillage depth and delaying tillage after harvest diminish soil disturbance (Goss et al. 1993) and consequently soil N release. Secondly, changes in the crop rotation such as the introduction of catch crops and spring crops can decrease SMN content during autumn and therefore reduce the risk of nitrate leaching after OSR. Justes et al. (1999) reported a significant reduction of SMN and nitrate leaching by a radish cover crop or volunteer OSR compared with bare soil.

Simulation modeling as a methodological approach for calculating N leaching from agricultural soils has become a common tool in agroecological research because a well-parameterized simulation model has some advantages for quantifying N leaching in agroecosystems compared to lysimeter studies or leachate sampling by suction cups because it is less labor intensive and expensive (Köhler et al. 2006). Sometimes the results are also less biased than results from lysimeter studies because the primary observations can be done under undisturbed soil conditions. Furthermore a simulation model is able to analyze different sites, many trial plots or larger scales. Additionally, the experimental data are accessible to a more intensive analysis of the processes influencing N leaching such as the components of the soil water budget or the mineralization rates. Several model approaches deal with N dynamics after OSR harvest, especially in terms of crop residue decomposition [Mueller et al. 1997 (DAISY); Mary et al. 1999 (LIXIM); Trinsoutrot et al. 2000 (NCSOIL); Nicolardot et al. 2001 (STICS)]. The present modeling approach differs from these earlier studies because it combines different submodels capable of calculating OSR residue decomposition, soil organic N mineralization as affected by tillage intensity, and crop N uptake, which range from a mechanistic to a descriptive character according to the availability of experimental data for parameterization and the degree of process understanding. The integration of these submodels into a system model within a simulation environment (Kage and Stützel 1999) providing parameter estimation and statistical evaluation techniques that allowed the quantification of effects of different management practices on soil N dynamics and N leaching on the cropping system level by calculating variables which cannot be directly measured, such as N leaching, and by empirically identifying parameter values of key equations.

Data from a 2-year field trial were used for initialization and parameterization of the model. To test the general applicability and the functionality of the model and the parameterization, it was validated on field measurements of an independent 5-year dataset.

Materials and methods

Field trials

Two different field trials carried out at the same site but in different years were used within this study to calibrate and validate the simulation model: a 2-year experiment (two experimental years, 2005/2006 and 2006/2007) and a subset (four experimental years 1992/1993, 1993/1994, 1994/1995, and 1997/1998) of a long-term experiment. The 2-year experiment was specially designed to study rotational and tillage effects on soil nitrogen dynamics after oilseed rape, whereas the long-term experiment had broader aims.

Site and weather conditions

The field trials were established on two fields of the Hohenschulen Experimental Station of the University of Kiel, located in NW Germany, 15 km west of Kiel.

The soil is a pseudogleyic sandy loam (Luvisol: 170 g kg^{-1} clay, pH 6.7, 9 mg kg^{-1} P, 15 mg kg^{-1} K, 13 g kg^{-1} C_{org}). The climate can be described as humid. Long-term total rainfall averages 750 mm annually, with ~400 mm received during April–September, the main growing season, and ~350 mm during October–March. Precipitation and temperature during the experimental periods are given in Table 1.

Design of the field experiment used for model calibration

The field trial started in autumn 2003. In this paper results of the percolation periods 2005/2006 and 2006/2007 are presented. The treatments was comprised of different soil tillage operations and subsequent crops after OSR (Table 2), arranged in a split-plot design. In treatment VOSR, volunteer OSR was grown as a catch crop after harvest, whereas *Phacelia tanacetifolia* (Phacelia) was grown as a catch crop in treatment CC. In treatments WWCT and WWMT, winter wheat was grown after OSR, with shallow tillage operations in WWMT compared with ploughing in WWCT. The treatments were randomized to the main plots; the randomized N treatments for OSR within the main plots formed four subplots. Only in the WWCT treatment were all four N treatments (N1 = 0 kg N ha^{-1}, N2 = 160 kg N ha^{-1}, N3 = 200 kg N ha^{-1}, N4 = 240 kg N ha^{-1}) considered; in the other treatments, detailed investigations were only carried out at the N3 level. Management treatments were compared at N3 whereas the effect of fertilization level was investigated only in WWCT. Plot size was 12 m × 12 m, and the subplot size was 3 m × 12 m. The four randomized N treatments were subplots within the main plots. N was applied as calcium ammonium nitrate with 27% N and varied in amount and distribution. Fungicides and other crop management measures not involving the treatments (e.g., herbicides and sowing date) were handled in accordance with the farmers' normal practice. At crop maturity, an area of 10.5 m^2 was harvested by combine harvester and yield was standardized to t ha^{-1} at 91% dry matter. Tillage depth in autumn was 10 cm with the compact disc cultivator, 20 cm with the cultivator, and 30 cm with the plough.

Plant and soil sampling

Plant samples were taken from OSR (0.5 m^2) in VOSR (N3), WWCT (N1, N2, N3, N4), and WWMT (N3) at harvest. Because of identical crop husbandry the crop residues in VOSR were assumed to be equal to CC. Total number of plants, dry matter of stems and pod walls, and corresponding C and N concentrations were determined at harvest (C/N-Analyser Vario MAX, CN Elementar Analysesysteme). For model calculations C and N amounts in the rooting system as well as the

Table 1 Precipitation and temperature at the Hohenschulen experimental station during the experimental periods and in the long term

Month	Experimental period					
	2005/2006		2006/2007		Long term	
	Temp. (°C)	Rain (mm)	Temp. (°C)	Rain (mm)	Temp. (°C)	Rain (mm)
July	18.0	92	20.8	53	16.9	100
August	16.9	49	18.6	143	17.9	59
September	15.3	20	16.9	33	14.2	61
October	11.8	67	12.5	80	9.8	75
November	5.8	44	7.5	44	4.9	58
December	2.8	46	6.3	39	1.6	62
January	−0.6	14	5.1	118	1.2	48
February	1.6	22	3.0	35	2.0	50
March	0.8	47	6.5	44	3.4	44
April	6.7	50	10.0	2	8.0	44
Sum rain		451		591		601

Table 2 Treatments in the field trial (OSR N fertilization level 200 kg N/ha; in treatment 4: 0, 160, 200, 240 kg N/ha)

Date		Treatment			
2005/2006	2006/2007	VOSR	CC	WWCT	WWMT
		Oilseed rape (cv. Trabant) harvest			
26/7/2005	28/7/2006	Compact disc cultivator		Compact disc cultivator	
26/8/2005	6/8/2006		Cultivator		
26/8/2005	7/8/2006		Rotary harrow/seed drill		
		Volunteer oilseed rape	Catch crop (Phacelia) (cv. Angelina)		
					Glyphosate
5/9/2005	12/9/2006			Cultivator	Compact disc cultivator
14/9/2005	14/9/2006			Plough	Compact disc cultivator
16/9/2005	15/9/2006			Rotary harrow/ seed drill	
				Winter wheat (cv. Tommi)	
	15/3/2007	Glyphosate[a]			
18/4/2006		Cultivator			
19/4/2006		Rotary harrow/seed drill			
		Oats (cv. Flämingsprofi) Maize (cv. Ronaldinio)[a]			

[a] Only in 2007

Abbreviations: OSR, Oilseed rape; VOSR, voluntary oilseed rape; CC catch crop (*Phacelia tanacetifolia*); WWCT, winter wheat conventional tillage; WWMT, winter wheat minimum tillage

shoot-to-root ratios were assumed to be similar to those given in Gosse et al. (1999). In the subsequent winter wheat (WWCT and WWMT), plant samples (0.25 m^2) were taken at the end of autumn growth and the beginning of spring growth. Total number of plants and shoots, total above ground dry matter, and N concentration were measured. In volunteer OSR (VOSR) and the catch crop (CC) total aboveground dry matter (0.25 m^2) and its N concentration were quantified fortnightly from emergence to end of autumn growth. N concentration was determined using near-infrared spectrometry (NIRS 5000, Foss).

Soil mineral nitrogen (NO_3–N plus NH_4–N: SMN) was investigated monthly in the period 2005/2006 apart from during snow cover or freezing. Four cores per plot, mixed into one sample, were taken to a depth of 90 cm in 30-cm layers. Additionally, soil samples (0–30 cm) were taken fortnightly in CC in autumn. In 2006/2007 soil mineral nitrogen was determined weekly (0–30 cm) and monthly (0–90 cm) in all treatments. Soil samples for SMN were put into a polyethylene bag, which was carefully closed and immediately cooled on the field using a cooling bag and thereafter stored frozen until analysis. After thawing overnight at room temperature, NO_3–N and NH_4–N were extracted using 0.0333 N $CaCl_2$ and analyzed colorimetrically. A subsample was oven-dried to determine the gravimetric soil moisture content.

Basic data of the field trial as amounts of crop residues, their C and N content, SMN, and crop N uptake were used for initialization and parameterization of the simulation model.

Design of the field experiment used for model evaluation

The model evaluation was carried out using the independent data from a long-term experiment laid out for optimizing nitrogen management in an oilseed rape—winter wheat—winter barley rotation and to study environmental effects. Measurements of the key parameters of the nitrogen pools in the soil plant system were taken but less frequently than in the parameterization experiments. This field trial was comprised of, beside other treatments, similar N fertilization levels and tillage systems after OSR harvest (conventional and minimum). A subset of data (four experimental years, 1992/1993, 1993/1994, 1994/1995, and 1997/1998) containing SMN, soil water, and plant N uptake values was used. It is presented in more detail by Sieling et al. (1999).

Statistical analysis

Analyses of variance were performed at $P = 0.05$ using the general linear model (GLM) procedure of the SAS statistical software package (SAS Institute Inc 1989).

Model

The model was used to simulate the N dynamics in the soil system in the different management treatments after OSR harvest. The main objective was the quantification of N losses via leaching in the different treatments by model calculation.

Water transport and evapotranspiration

The submodels which describe the water movement through the soil and evapotranspiration were presented in detail by Kage et al. (2003) and Kage (2000). Roughly, the water transport model calculates soil water movement by using the water-content-based formulation of the Richard's equation. Relationships between soil water diffusivity and the volumetric water content are described by the functions of van Genuchten (1980) in the revised form of Wösten and Van Genuchten (1988). Parameters for this relationship were estimated with the program RETC (Van Genuchten et al. 1991) after characterizing soil water retention data, soil texture, and bulk density. The derived parameter values are given in Table 3. Potential evapotranspiration is calculated using the Penman–Monteith equation (Monteith 1973) using a standard stomata resistance of 50 s m^{-1}, which was converted into a canopy resistance using the approach of Stockle et al. (1994).

In order to consider delayed water influx into the soil after snow fall a submodel of snow accumulation was adopted from the DAISY model (Hansen et al. 1991), which is based on the model of Jansson and Haldin (1980). Basic parts of this submodel are the separate calculation of liquid water and total water expressed in equivalent water within the snow pack:

$$W_l = W_l + [R + M - E_l - J]\Delta t, \quad (1)$$

$$W_t = W_t + [S + R - E_t - J]\Delta t, \quad (2)$$

where W_l is the liquid water, W_t total water, R precipitation as rain, S precipitation as snow, M melted snow, E_l the evaporation from snow, E_t the evaporation and sublimation from snow, and J the liquid water efflux from the snow pack.

Mineralization

The submodel for mineralization of crop residues and soil organic matter is a simplified modification of the model of Verberne et al. (1990). This simplification was motivated by the aim of reducing the number of parameters within this submodel drastically while maintaining the ability to describe the dynamics of nitrogen immobilization by crop residues with wide C/N ratios. This simplification ended up with a model containing only four organic carbon pools, C_i: soil organic matter, C_{som}; microbial biomass, C_{biom}; easily decomposable crop residues, C_{dpm}; and more resistant crop residues, C_{rpm} (Fig. 1). All these pools have fixed C/N ratios and decompose by first-order kinetic processes:

$$\frac{\mathrm{d}C_i}{\mathrm{d}t} = -k_i C_i f_j, \quad (3)$$

where k_i are the rate coefficients of the four C pools and f_j $(0 < f < 1)$ is a factor describing abiotic

Table 3 Parameters of the Van Genuchten equations

Soil	Depth (cm)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm day^{-1})
Sandy loam	0–30	0	0.3865	0.04571	1.190	60
	30–60	0	0.3837	0.06415	1.177	60
	60–90	0	0.4017	0.08271	1.183	50

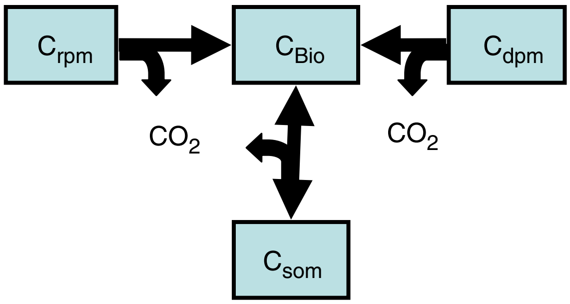

Fig. 1 Carbon pools and flows in the mineralization submodel

limitations of temperature (f_T) and soil water content (f_W). Net mineralization of each pool is then determined by multiplying with the N/C ratio:

$$\frac{dN_i}{dt} = \frac{dC_i}{dt}\frac{N_i}{C_i}. \tag{4}$$

Gross microbial growth is the product of the mineralization rate and the efficiency E (Kage 2000) with which C is used for the synthesis of organic components. Subtracting the decomposition of the microbial biomass yields the net microbial growth:

$$\frac{dC_{biom}}{dt} = E\sum k_i C_i f - k_{biom} C_{biom} f. \tag{5}$$

The net mineralization rate of each pool i is the result of decomposition organic nitrogen and nitrogen immobilization by microbial growth:

$$\frac{dN_{min,i}}{dt} = k_i C_i f\left(\left(\frac{N}{C}\right)_i - E\left(\frac{N}{C}\right)_{biom}\right). \tag{6}$$

If, as in our model, only two pools of decomposing plant residues (C_{dpm} and C_{rpm}) with fixed C/N ratios are considered, the allocation of the total carbon in crop residues (C_{CR}) to both pools can be easily calculated from C_{CR}, the CN ratios of both crop residue carbon pool (CN_{dpm} and CN_{rpm}) and the total amount of nitrogen in the crop residues (N_{CR}) (Kage 2000):

$$f_{dpm} = \left(\frac{-N_{CR} CN_{dpm} CN_{rpm}}{C_{CR}} + CN_{dpm}\right) \times \frac{1}{-CN_{rpm} + CN_{dpm}}. \tag{7}$$

Also shortage of mineral nitrogen affecting the decomposition processes is considered by the reducing factor f_{SMN} in the model for all decomposition processes which immobilize inorganic nitrogen. The reducing process follows are Michaelis–Menten kinetic where K_{SMN} is set at a value of 1 kg N ha^{-1}/10 cm:

$$f_{SMN} = \min\left(1, \max\left(0, \frac{(SMN - SMN_{crit})}{(SMN - SMN_{crit}) + K_{SMN}}\right)\right). \tag{8}$$

The introduction of the factor f_{SMN} is also technically motivated, because otherwise an iteration concept has to be introduced in order to prevent negative SMN values.

For further details of the mineralization submodel see Kage (2000). When crop residues are added to the soil they are assumed to decompose at the surface layer with a 50% lower decomposition rate compared with incorporation into the first soil layer.

The impact of tillage operations on soil nitrogen dynamics is included into the mineralization submodel in a simple descriptive way by introducing a factor f_{Till}. It is assumed that a tillage operation increases mineralization rates by adding a certain value, Min_{eff}, to f_{Till}, which then boosts the decomposition rate in the tilled soil layer:

$$f_{Till} = f_{Till} + Min_{eff}, \tag{9}$$

$$\frac{dC_i}{dt} = -k_i C_i f_j f_{Till}. \tag{10}$$

The tillage effect, however, is assumed to affect mineralization rates only for a certain time span. Therefore, a factor d_{Till}, describing the decay rate of f_{Till} with time is introduced:

$$\frac{df_{Till}}{dt} = -d_{Till}(f_{Till} - 1). \tag{11}$$

The value of d_{Till} was set to 0.05 (1/d).

This approach is comparable to the results of La Scala et al. (2008) regarding the effects on differences of mineralization rates between tillage treatments, though the implementation is somewhat different.

When tillage operations are carried out, crop residues are buried in the soil, and the amounts of the four carbon pools are equally distributed within the tilled soil layer.

Vertical nitrate transport

In well-aerated soils the concentration of ammonium is usually very low compared with that of nitrate. Therefore only nitrate nitrogen is considered in the model. Nitrate transport in the soil profile is calculated by a numerical solution of the convection–dispersion equation (Addiscott and Wagenet 1985). The initial condition for this equation was the measured SMN from 0 to 90 cm which was determined in a spatial resolution of 30 cm soil layers. The spatial, vertical discretization was 10 cm and measured initial SMN was distributed evenly between three layers.

Plant N uptake

Plant N uptake of wheat, volunteer oilseed rape, and *Phacelia* was calculated using an empirical function fitted to the experimental data. For winter wheat, volunteer OSR, and *Phacelia* a logistic growth curve is fitted to the measured data

$$\frac{\mathrm{dN}}{\mathrm{d}t} = k_3 N T_{\mathrm{eff}} \left(1 - \frac{N}{N_{\max}}\right), \qquad (12)$$

where k_3 is a growth rate parameter, T_{eff} the effective temperature, and $N_{\max}$ the maximum N uptake. The start value N_0 was set at 0.001 kg N ha^{-1}. T_{eff} was calculated from

$$T_{\mathrm{eff}} = \max(0, (T_{\mathrm{a}} - T_{\mathrm{b}})), \qquad (13)$$

where T_{a} is the daily average air temperature and T_{b} is the base temperature, assumed to be 3°C.

Similar procedures were used to fit measured data of leaf area index (LAI), crop height, and crop dry matter. The latter is needed to estimate growth rates of a simple root system submodel, which describes temporal and spatial root length density distribution (Kage et al. 2004).

Parameter estimation and statistical evaluation

The above algorithms were implemented as submodels within the HUME modeling environment (Kage and Stützel 1999), which supports parameter estimation based on the Marquardt algorithm (Marquardt 1963).

Analyses of the residual errors for statistical evaluation (observed value minus estimates value) were done using the statistical measures modeling efficiency (EF) and root mean square (RMSE). EF (Smith et al. 1997) is described as

$$\mathrm{EF} = 1 - \frac{\sum (y_i - \widehat{y}_i)^2}{\sum (y_i - \bar{y})^2}, \qquad (14)$$

where y_i is the value of the i-th observation, $\widehat{y}_i$ is the i-th model prediction, and $\bar{y}$ is the average of the observations. The maximum value of the EF occurs for complete agreement between the simulated and measured values, but negative values are also possible if the model describes the data less well than the observation mean.

The other statistical parameter used in this study is the RMSE

$$\mathrm{RMSE} = \sqrt{\frac{\sum (y_i - \widehat{y}_i)^2}{n}}, \qquad (15)$$

giving the average absolute model prediction error.

Results

Carbon and nitrogen pool sizes at harvest of OSR

At harvest of OSR dry matter (DM) of the crop residues, C in crop residues and the C/N ratio did not differ at $P = 0.05$ between the four treatments fertilized at N3 (200 kg N ha^{-1}) (Table 4). The years significantly affected N in crop residues at harvest. The different N fertilization levels in the WWCT treatment significantly influenced the measured and calculated parameters. In both years DM at N2 and N3 but not at N4 was significantly higher than at N1 (Table 5). The lower DM values of N4 were associated with lower seed yields compared with N2 and N3 in 2006 (data not shown). In 2007 seed yield of N4 was lower than in N3 (data not shown). Comparing both years, DM was significantly higher in 2007 at all fertilization levels, as well as C and N in crop residues except at N1. C and N in crop residues were similar at N2, N3, and N4, but were significantly higher than at N1 in both years. SMN at harvest rose with increasing fertilization and was significantly higher in N4 (Table 5).

Soil water dynamics after harvest of OSR

Due to heavy rainfalls after harvest in 2006 the soil profile was refilled with water earlier than in autumn 2005, although the initial soil water content was much lower at harvest in 2006. Therefore the percolation period started about 1 month earlier in autumn 2006 in this treatment as indicated by the simulated drainage rate (Fig. 2). Key data of the soil water balance are presented in Table 6. Simulated drainage was higher in

Table 4 Measured values of C in crop residues, N in crop residues, C/N ratio, DM in crop residue, and SMN at harvest in the different treatments (N3)

Year	Treatment	C in crop residues (kg C ha^{-1})	N in crop residues (kg N ha^{-1})	C/N ratio	DM in crop residue (kg DM ha^{-1})	SMN at harvest (kg N ha^{-1})
2006	VOSR	4,240	68	62	9,790	79
	CC	4,240[a]	68[a]	62[a]	9,790[a]	79[a]
	WWCT	4,440	75	61	10,120	53
	WWMT	4,080	73	55	9,380	74
2007	VOSR	5,410	112	48	12,390	55
	CC	5,410[a]	112[a]	48[a]	12,390[a]	55[a]
	WWCT	5,280	87	61	11,870	52
	WWMT	4,400	81	54	9,920	50
$LSD_{0.05}$ treatment		ns	ns	ns	ns	ns
$LSD_{0.05}$ year		ns	17.20	ns	ns	16.18
$LSD_{0.05}$ treatment × year		ns	ns	ns	ns	ns

CC (catch crop) omitted for statistical analyses

[a] CC = VOSR (voluntary oilseed rape)

OSR, oilseed rape; VOSR, voluntary oilseed rape; CC catch crop (*Phacelia tanacetifolia*); WWCT, winter wheat conventional tillage; WWMT, winter wheat minimum tillage; LSD, least significant difference

Table 5 Measured values of C in crop residues, N in crop residues, C/N ratio, DM in crop residue, and SMN at harvest in the treatment winter wheat conventional tillage (WWCT) (N1, N2, N3, N4)

Year	Treatment	N fertilization level	C in crop residues (kg ha^{-1})	N in crop residues (kg N ha^{-1})	C/N ratio	DM in crop residue (kg DM ha^{-1})	SMN at harvest (kg N ha^{-1})
2006	WWCT	1	2,430	35	70	5,610	45
	WWCT	2	4,050	61	66	9,220	56
	WWCT	3	4,440	75	61	10,120	53
	WWCT	4	3,890	69	57	8,890	98
2007	WWCT	1	3,420	28	122	7,640	31
	WWCT	2	5,100	83	61	11,440	33
	WWCT	3	5,280	87	61	11,870	52
	WWCT	4	4,680	98	48	10,520	75
$LSD_{0.05}$ fertilizer level			1,409	21	8.8	21	35
$LSD_{0.05}$ year			700	11	11	1,579	ns
$LSD_{0.05}$ fertilizer level × year			ns	ns	13	ns	ns

2006/2007 because of 140 mm more rainfall during the observation period.

The model reproduced soil water dynamics in the 0–90 cm layer with an RMSE of 2.05 vol.%. In the layer 0–30 cm RMSE was 3.25 vol.%, in 30–60 cm 2.39 vol.%, and in 60–90 cm 3.77 vol.%. EF was highest in the whole profile (0.80) and lowest in the horizon 60–90 cm (0.37) (Table 7).

The dynamics of soil water, cumulative precipitation, cumulative evapotranspiration, and cumulative drainage water in both years in WWCT at N3 are shown in Fig. 2. The model calculated ~30–50% less drainage water in the two treatments with a catch crop (VOSR, CC), because the catch crops used more water for transpiration. The amount of drainage water was also influenced by the amount of soil water in the profile (0–90 cm) at harvest. The different amounts of soil water we found at harvest in WWCT can be explained by the varying OSR canopies due to different N fertilization levels.

Fig. 2 Measured and simulated soil water content, measured precipitation, simulated evapotranspiration, and simulated drainage rate in the WWCT treatment (N3) during the simulation periods 2005/2006 (**a**) and 2006/2007 (**b**) from the calibration data set

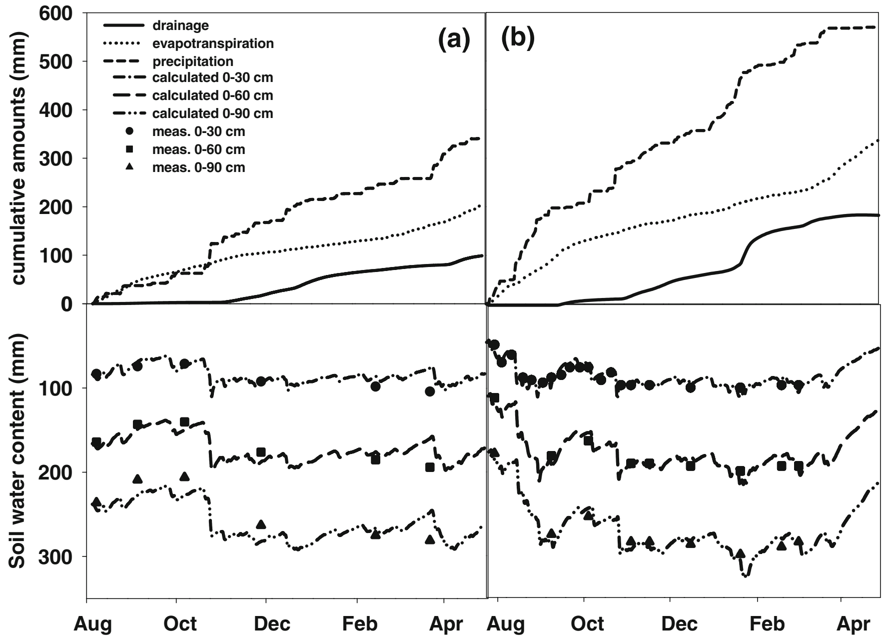

Table 6 Soil water (0–90 cm) at harvest, cumulative precipitation, cumulative evapotranspiration, cumulative drainage, and soil water (0–90 cm) at the end of simulation in all treatments

Year	Treatment	N level	Soil water (0–90 cm) at harvest (mm) measured	Cum. precipitation (mm) measured	Cum. evapotrans. (mm) calculated	Cum. drainage (mm) calculated	Soil water (0–90 cm) at the end of simulation (mm) calculated
2005/2006	VOSR	3	243	343	296	36	261
	CC	3	243		281	45	261
	WWCT	1	279		252	108	261
	WWCT	2	252		246	84	261
	WWCT	3	243		219	100	261
	WWCT	4	261		248	91	261
	WWMT	3	243		231	91	261
2006/2007	VOSR	3	117	570	378	100	216
	CC	3	117		356	106	225
	WWCT	1	171		365	183	198
	WWCT	2	135		362	148	198
	WWCT	3	171		364	184	198
	WWCT	4	144		362	153	198
	WWMT	3	108		322	148	207

Soil mineral N, net mineralization, and N leaching after harvest of OSR

The mineralization submodel was parameterized in a first step using a parameter set for decomposition of OSR residues taken from Mueller et al. 1997. The rate constant k_{rpm_biom} was then was slightly adjusted by "eye fitting" to the observed SMN values whereas the parameter k_{dpm_biom} was retained at 0.05. The parameters k_{som_biom} and k_{biom_som} were optimized by

Table 7 Statistical measures of a linear regressions (measured versus simulated) for soil water content in the different soil layers in the different soil layers in the experimental years 2005/2006 and 2006/2007

Depth (cm)	*n*	Slope	Intercept	r^2	RMSE (Vol. %)	EF
0–30	186	0.755* (±0.040)	5.95* (±0.11)	0.66*	3.25	0.57
30–60	105	0.900* (±0.049)	1.98* (±0.014)	0.76*	2.39	0.71
60–90	105	0.684* (±0.065)	9.58* (±0.018)	0.52*	3.77	0.37
0–90	105	0.961* (±0.047)	1.20* (±0.013)	0.80*	2.05	0.80

±, Indicates s.e.; * indicates significance at $P = 0.05$ for slope $\neq 1$ intercept $\neq 0$ and significance of the *F* value for the linear regression

Table 8 Decomposition parameters for different pools of the mineralization submodel

Parameter	Pool	Description	C/N ratio	k (day^{-1})	Efficiency
$k_{\text{biom\_som}}$	C_{biom}	Microbial biomass	6	0.004544	1
$k_{\text{dpm\_biom}}$	C_{dpm}	Fraction of easily decomposable residues	6	0.05	0.69
$k_{\text{rpm\_biom}}$	C_{rpm}	Fraction of resistant residues	120	0.003	0.3
$k_{\text{som\_biom}}$	C_{som}	Soil organic matter	10	0.000329	0.5

See text for explanation of the parameter names

minimizing the sum of the squared differences between measured and simulated SMN values of all treatments and years. Also the parameters for the submodel describing the influence of tillage operations on the decomposition rates were estimated by "eye fitting" and resulted in values for $\text{Min}_{\text{eff}} = 5(-)$ and for $d_{\text{Till}} = 0.05$ (day^{-1}). A simultaneous estimation of all parameters was not feasible, because of the limited information included in the available experimental data. The optimized rate constants of the mineralization submodel after optimization are presented in Table 8.

Using to the obtained parameter values, the model calculated a rapidly decomposition of the incorporated OSR residues. By October 20, 40% of the C added to the soil as crop residues had decomposed. By the end of the simulated time span, 30–50% of the crop residues had decomposed, depending on the year (data not shown).

The statistical evaluation of the model after calibration with regard to SMN was quite good (Table 9) considering the high spatial variability of soil conditions at the experimental site. In the whole profile the model reproduced SMN dynamics with an RMSE of 14 kg SMN ha^{-1} and an EF of 0.52. However, the coefficients of determination and the EF in the single soil layer also decreased. In the 60–90 cm level, the EF was even negative. SMN was overestimated by the model compared with the data measured in the field. Soil N dynamics of WWMT in both simulation periods and WWCT N3 and CC in 2005/2006 are presented in Figs. 3 and 4. The model simulation resulted in strongly different N leaching values between the years and the treatments. Due to the lower drainage rates in 2005/2006 (Table 6) mean N leaching was lower during this period. In both simulation periods N leaching was highest in WWCT N4 (38 and 37 kg N ha^{-1}) and lowest in CC (7 and 7 kg N ha^{-1}) (Table 10). Comparing the treatments at N3, smaller differences in N leaching between the treatments were observed (Table 10). The low amount of leached N in WWCT in 2005/2006 can be explained against the background of 20 kg less SMN at harvest in this treatment compared with the other treatments at the same fertilization level. Growing volunteer OSR or *Phacelia* as a catch crop after harvest led to lower rates of N leaching than in the other treatments at the same fertilization level. Figure 4 shows that the delay of N leaching in CC reduced the amount of leached N compared with WWCT. The minimum tillage strategy in WWMT reduced N leaching in 2006/2007 by 19 kg N ha^{-1}. Although SMN at harvest was 21 kg N ha^{-1} higher than in WWCT, N leaching in WWMT was not increased (difference 1 kg N ha^{-1}) (Table 10). Simulated net mineralization was strongly affected by the years. The higher precipitation and temperatures in 2006/2007 (Table 1) increased net mineralization in all treatments compared with 2005/

Table 9 Statistical measures of a linear regression (measured versus simulated), root mean squared error (RMSE), and modeling efficiency (EF) for SMN in the different soil layers in the experimental years 2005/2006 and 2006/2007 of the calibration data set and of the evaluation data set

Depth (cm)	N	Slope	Intercept	r^2	RMSE (kg SMN ha^{-1})	EF
Calibration data set						
0–30	186	0.72* (±0.076)	9.21* (±1.85)	0.41*	10	0.26
30–60	105	0.74* (± 0.083)	1.48$^{n.s.}$ (±1.46)	0.47*	6	0.27
60–90	105	0.47* (±0.083)	3.33* (±1.46)	0.26*	6	−0.82
0–90	105	0.85* (±0.083)	6.12$^{n.s.}$ (±4.35)	0.53*	14	0.52
Evaluation data set						
0–30	72	0.83*(±0.074)	4.17* (±1.47)	0.64*	6	0.60
30–60	72	0.70* (±0.071)	1.85$^{n.s.}$(±1.16)	0.58*	5	0.29
60–90	66	0.64* (±0.084)	−0.30$^{n.s}$ (±1.46)	0.47*	8	−0.72
0–90	66	0.68* (±0.065)	8.63* (±3.45)	0.63*	14	0.26

±, Indicates s.e.; * indicates significance at $P = 0.05$ for slope ≠ 1, intercept ≠ 0 and significance of the F value for the linear regression

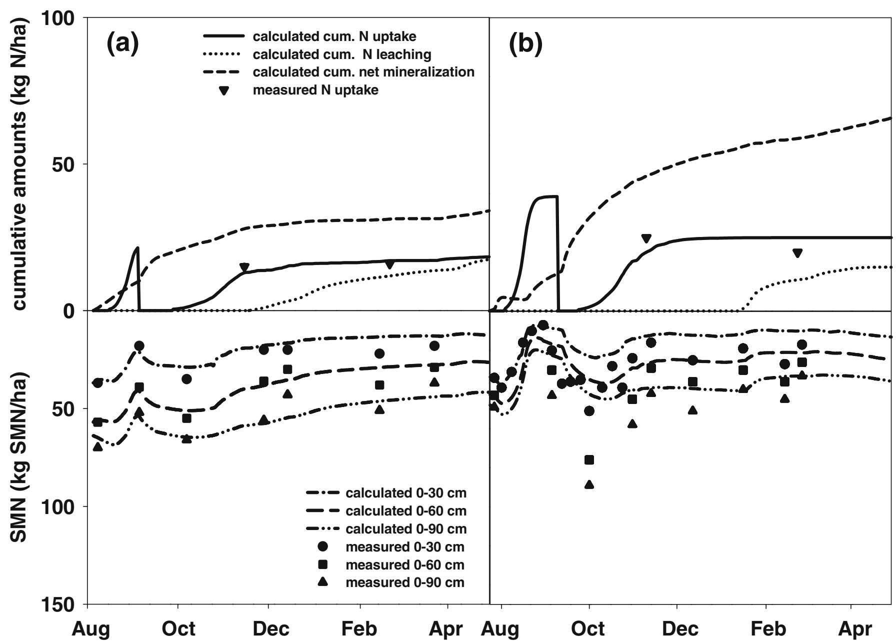

Fig. 3 Measured (symbols) and simulated (lines) soil mineral nitrogen, measured (symbols) and calculated (lines) N uptake, simulated net mineralization, and simulated N leaching in the treatment WWMT during the simulation periods 2005/2006 (**a**) and 2006/2007 (**b**) from the calibration data set

2006. Due to the one-time shallow tillage operation after harvest in VOSR the net mineralization during the simulation periods was diminished compared with the other treatments with more intensive tillage operations. In CC an intensive tillage operation with a cultivator was carried out after harvest, and therefore net mineralization was as high as for the ploughed treatments. However, these tillage operations were shortly after OSR harvest and were compensated by the high N uptake of the catch crop *Phacelia*, leading to a low N leaching loss. Nevertheless, despite the low N leaching values in the catch crop treatments, especially in VOSR, the EU drinking water threshold of 50 ppm nitrate was exceeded remarkably due to the lowest amounts of drainage water (Table 6). The results also clearly show the influence of overfertilization

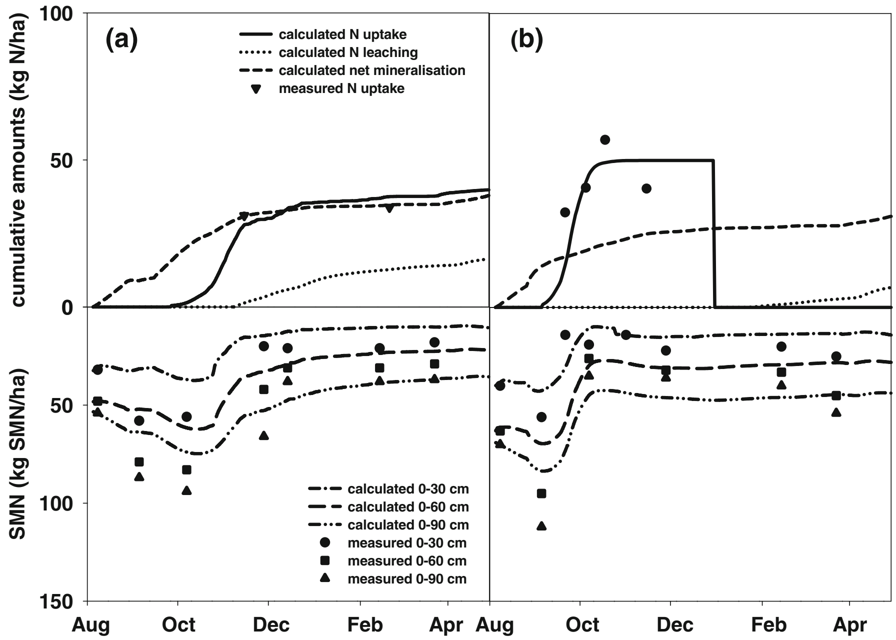

Fig. 4 SMN dynamics, N uptake, net mineralization, and N leaching in treatment WWCT (**a**) and CC (**b**) in the simulation period 2005/2006

Table 10 Measured and simulated key data of the N dynamics after OSR for different treatments comprising tillage practices and crop rotations

Year	Treatment	N level	SMN at harvest (kg SMN ha^{-1}) measured	N uptake at the end of autumn growth (kg N ha^{-1}) measured	SMN (0–90 cm) at the end of autumn growth (kg SMN ha^{-1}) measured	Cum. net mineralization (kg N ha^{-1}) calculated	Cum. N leaching (kg N ha^{-1}) calculated	NO_3 concentration in drainage water (ppm) calculated
2005/2006	VOSR	3	79	37	31	17	11	138
	CC	3	79	40	36	31	7	67
	WWCT	1	45	27	48	35	13	52
	WWCT	2	56	43	65	27	10	52
	WWCT	3	53	30	66	38	16	71
	WWCT	4	98	36	74	39	38	182
	WWMT	3	74	14	56	34	17	84
2006/2007	VOSR	3	55	44	25	34	14	62
	CC	3	55	58	21	47	7	28
	WWCT	1	31	32	17	55	14	33
	WWCT	2	33	29	32	47	16	49
	WWCT	3	52	33	24	61	34	81
	WWCT	4	75	35	37	62	37	106
	WWMT	3	50	25	42	66	15	44

See Table 2 for explanation of abbreviations

in treatment WWCT at N4. The high input of fertilizer N increased SMN at harvest and consequently N leaching and N concentrations in drainage water. The EU threshold was only met in CC, WWMT, and the reduced N fertilization levels of WWCT in 2006/2007.

Model evaluation

The parameters of the statistical evaluation of the evaluation data (SMN) are shown in Table 9. The model reproduced the dynamics in the whole profile (0–90 cm) with an RMSE of 14 kg SMN ha^{-1}. The EF of 0.26 was lower compared with the calibration data. In the 60–90 cm layer the EF value was negative (−0.72), indicating poor model prediction of SMN values in that depth.

Discussion

The aim of this study was to quantify N leaching losses after growing OSR by combining a field trial and a model approach for different treatments after OSR harvest. For this purpose we used a simulation model comprised of model modules for soil water dynamics, the mineralization processes of soil organic N and crop residue N, effects of tillage, and N uptake by the subsequent crop to oilseed rape. This methodological approach of simulation modeling has the advantage that regularly field-measured SMN data combined with soil moisture data can be used for calculating N leaching (Mary et al. 1999; Köhler et al. 2006). Additionally, the experimental data are accessible for a detailed analysis of the different processes influencing nitrate leaching in the cropping system studied, such as the components of the soil water budget, the mineralization rate, the crop residues decomposition, and the SMN dynamics after OSR harvest. The model modules differed in their level of detail and their degree of mechanistic character. Whereas the nitrogen uptake of the crops following winter wheat was simulated using a simple logistic growth equation fitted to experimental data, the soil water balance calculation is based on well-accepted mechanistic approaches, i.e., the Penman–Monteith and the continuity equation approach. The soil mineralization submodel is somewhat in between these extremes. It is based on carbon fluxes and therefore able to predict immobilization of nitrogen during the decomposition process of crop residues, but it consists of a relatively small number of carbon pools and is therefore probably not appropriate for the prediction of mineralization processes over a wider range of soil conditions. However, due to the small number of pools only a few parameter values have to be identified. This was done in the present study by taking some values from comparable mineralization models and by direct parameter estimation from measured SMN data. After slight adaptations the parameter set of the mineralization submodel taken from Mueller et al. (1997) were applicable to our data. Tillage effects were modeled in a very simple empirical way, by introducing a tillage factor which increases decomposition rates for a limited time.

In the present study the complex interactions of residue decomposition, different tillage intensities, and subsequent crop growth were investigated. Water dynamics could be reproduced very well by the model. In the whole profile (0–90 cm) the RMSE was 2.05 vol.% or 18.45 mm in both years. Also the SMN dynamics were reproduced well in the whole profile (0–90 cm) with an RMSE of 14 kg SMN ha^{-1} but in the 60–90 cm layer the model performance was not entirely satisfactory. Additionally, the strong increase of SMN after tillage operations could often not be reproduced by the model. In the 60–90 cm layer the model overestimated SMN and therefore also N leaching to some extent. Several processes of N loss such as denitrification or preferential flow, which are very hard to measure with satisfactory precision and which are not considered in our model, could be reasons for this overestimation of the low SMN in deeper soil layers. Another explanation for this effect could be the large variability in soil properties due to heterogeneous soil at the experimental site, which originates from glaciofluvial parent material. Additionally, the precision of the sampling and analyzing method is questionable when SMN values were rather low like in the 60–90 cm layer (Aufhammer et al. 1989). The same authors reported also tremendous differences in SMN when sampling points and sample handling were varied.

Mary et al. (1999) and Justes et al. (1999) analyzed N dynamics after OSR harvest applying the LIXIM model to field measurements of three different treatments after OSR. The outcomes of the modeling study of Mary et al. (1999) resulted in low RMSE values for SMN content ranging from 2.4 to 5.7 kg SMN ha^{-1}. However, the conditions required for the application of this model were the absence of plant cover or a slowly growing crop transpiring little water, shallow rooting, and little N uptake (Mary et al. 1999). Additional management practices such as tillage were not carried out. Kersebaum (2007) modeled the N dynamics in a 6-year crop rotation using the HERMES model. The model outcomes for SMN (0–90 cm) resulted in an RMSE of 24.8 kg SMN ha^{-1}. It is obvious that, besides the validity of the model, the number of processes considered by a model and their complexity and interactions might have strong influence on the model performance. Nevertheless, keeping the restrictions and shortcomings of our approach in mind, the applied model is an efficient scientific tool for analyzing N dynamics after OSR harvest. It satisfactorily reproduced consistent results for the various treatments in the field trial regarding tillage operation, subsequent crop, and N fertilization level, resulting in different amounts of N leaching.

In the present study, increasing amounts of N fertilization to OSR strongly increased SMN at OSR harvest and in autumn. Several studies resulted in remarkably higher SMN values, sometimes exceeding 100 kg SMN ha^{-1}, at OSR harvest following a function of two straight lines if high amounts of N fertilizer were used (Shepherd and Sylvester-Bradley 1996; Sieling et al. 1999; Beaudoin et al. 2005; Makowski et al. 2005). Di and Cameron (2002) reported a threshold level of N fertilization above 200 kg N ha^{-1} which increased N leaching in arable cropping. Sieling and Kage (2006) stated a positive correlation between a simple N balance (N fertilization minus N offtake by the seed) and N leaching and between mineral N fertilization and N leaching. This positive correlation between excessive N fertilization and N leaching is also confirmed by our calculations. Amounts of N fertilizer above 200 kg N ha^{-1} led to a strong increase of N leaching whereas amounts below 200 kg N ha^{-1} differed only slightly. These results show the importance of more precise calculations of N fertilizer doses considering soil and OSR canopy properties.

The differences between the tillage treatments (WWCT versus WWMT) and winter wheat as the subsequent crop indicate that minimum tillage combined with a short period of growing volunteer OSR as a catch crop before sowing of winter wheat can decrease N leaching. These results agree with the findings of Lickfett (1993) and Goss et al. (1993) who reported about diminished SMN when tillage operation intensities in autumn were reduced or totally omitted after OSR harvest.

Due to the tillage operations, however, not only is the soil mixed but also OSR residues are incorporated into the soil. The C/N ratio in OSR residues under a regular fertilization regime of about 200 kg N ha^{-1} were about 50–60 (Table 4). Justes et al. (1999) and Mary et al (1999) report about N immobilization of about 20 kg N ha^{-1} after OSR residue incorporation (C/N = 54, N fertilization 270 kg N ha^{-1}). Jensen et al. (1997) observed a decrease of SMN of 18 and 25 kg SMN ha^{-1} after incorporation of 4 or 8 t OSR residues ha^{-1}, respectively. In addition, Trinsoutrot et al. (2000) stated that the N amounts mineralized from OSR residues and then returned to the subsequent crop are relatively small. According to these results, it is obvious that the incorporation of OSR residues by tillage operations after harvest lead to N immobilization depending on the amount and quality (C/N) of the residues. Because of missing treatments without residues the effect of straw incorporation could not be separated from tillage effects in the present study. Nevertheless, immobilization processes are taken into account in the carbon-based mineralization submodel. However, several studies showed that straw incorporation is an indispensable part of proper N management after harvest to prevent N leaching (Justes et al. 1999; Trinsoutrot et al. 2000; Beaudoin et al. 2005).

Growing catch crops to reduce the level of SMN and prevent N leaching is a common agronomic practice, especially in water protection areas. In the present study the establishment of the two catch crops after OSR harvest reduced N leaching, especially when *Phacelia* was grown. Lickfett (1993) recommended volunteer OSR to grow over winter without any tillage operation, thus reducing mineralization of soil-borne N and consequently N leaching. Using this strategy, the cumulative mineralization could be reduced in the present study compared with the treatments with winter wheat as the subsequent crop, but N leaching was still lower in the *Phacelia* treatments. Additionally, growing volunteer OSR is characterized by two disadvantages. Firstly, due to the low drainage rate, the nitrate concentration in the percolation water was raised remarkably and exceeded the EU drinking water threshold to a higher extent than the other treatments. Secondly, growing volunteer OSR could be critical because a high density of OSR in the rotation can promote pathogens and pests (Christen 2006). *Phacelia* took up most N in autumn, and N leaching and nitrate concentration were lowest in both years at the N3 fertilization level. However, growing catch crops combined with a spring crop is less profitable than cropping winter wheat, which is commonly grown after OSR, and therefore compensatory payments would be necessary especially in water protection areas. In 2005/2006 the EU drinking water threshold of 50 ppm nitrate was exceeded in all treatments. In 2006/2007 this threshold could be met in CC, WWMT, and the reduced N fertilization levels N1 and N2 of WWCT. It is obvious that the amounts of percolation water and consequently N leaching strongly depend on weather conditions. The present study indicates that the precise estimates of N fertilization rates combined with reduced tillage after harvest or growing a noncruciferous catch crop may be appropriate strategies to reduce N leaching and nitrate concentrations in percolation water.

Conclusion

Amounts of N leaching after growing OSR are higher than after cereals. In the present study possible strategies to reduce N leaching were investigated by combining a field trial and simulation modeling approach. The simulation model reproduced the N dynamics after OSR well and acted as an efficient scientific tool for investigating effects of management on N leaching. The results provide strong evidence that excessive amounts of fertilizer N increased SMN at harvest and therefore leaching potential. A proper calculation of N fertilizer rates is a first step towards prevent N losses. Growing the most profitable crop (winter wheat) after OSR with minimum tillage combined with a short-term volunteer OSR growth may be an appropriate practice to reduce N mineralization in autumn and to decrease N leaching to some extend in the range of environments we tested. Although SMN was immobilized in the course of OSR residue decomposition, ploughing or other intensive tillage operations should be avoided after OSR. Catch crops over winter and the introduction of spring crops have the greatest potential to reduce N leaching, but these strategies are combined with reduced economic returns compared with cropping winter wheat. Therefore minimum or zero tillage may reduce N leaching losses when establishing winter crops such as winter wheat with low N uptake in autumn after OSR.

Acknowledgements The authors would like to thank Mr. Ruediger Stroeh, Mrs. Gunda Schnack, Mrs. Cordula Weise, and Mrs. Kirsten Schulz and for their expert technical assistance.

References

Addiscott TM, Wagenet J (1985) Concepts of solute leaching in soils: a review of modeling approaches. J Soil Sci 36:411–424. doi:10.1111/j.1365-2389.1985.tb00347.x

Aufhammer W, Federolf K-G, Kempf H et al (1989) Variabilitätsursachen und Aussagemöglichkeiten der N_{min}-Methode (Variability and significance of the "N_{min}-procedure"). Landwirtschaftliche Forsch 42:281–292

Beaudoin N, Saad JK, van Laethem C et al (2005) Nitrate leaching in intensive agriculture in Northern France: effect of farming practices, soils and crop rotations. Agric Ecosyst Environ 111:292–310. doi:10.1016/j.agee.2005.06.006

Catt JA, Howse KR, Christian DG, Lane PW, Harris GL, Goss MJ (2000) Assessment of tillage strategies to decrease nitrate leaching in the Brimstone Farm Experiment, Oxfordshire, UK. Soil Tillage Res 53:185–200. doi:10.1016/S0167-1987(99)00105-1

Christen O (2006) Raps in der Fruchtfolge – ist die Grenze der Ausdehnung erreicht? (with english summary). UFOP-Schriften 29, Öl- und Proteinpflanzen. OIL 2005:119–128

Di HJ, Cameron KC (2002) Nitrate leaching in temperate agroecosystems: sources, factors and mitigation strategies. Nutr Cycl Agroecosyst 46:237–256. doi:10.1023/A:1021471531188

Goss MJ, Howse KR, Lane PW, Christian DG, Harris GL (1993) Losses of nitrate nitrogen in water draining from under autumn-sown crops established by direct drilling or mouldboard ploughing. J Soil Sci 44:35–48. doi:10.1111/j.1365-2389.1993.tb00432.x

Gosse G, Cellier P, Denoroy P et al (1999) Water, carbon and nitrogen cycling in a rendzina soil cropped with winter oilseed rape: the Châlons oilseed rape database. Agronomie 19:119–124. doi:10.1051/agro:19990204

Hansen S, Jensen HE, Nielsen NE et al (1991) Simulation of nitrogen dynamics and biomass production in winter wheat using the Danish simulation model DAISY. Fert Res 27:245–259. doi:10.1007/BF01051131

Jansson PE, Haldin S (1980) Soil water and heat model. Technical description. Technical Report 26, 1980. Swedish Coniferious Forest Project, Department of Ecology and Environment Research, Swedish University of Agricultural Science, Uppsala, Sweden

Jensen LS, Mueller T, Magid J et al (1997) Temporal variation of C and N mineralization, microbial biomass and extractable organic pools in soil after oilseed rape straw incorporation in the field. Soil Biol Biochem 29:1043–1055. doi:10.1016/S0038-0717(97)00014-X

Justes E, Mary B, Nicolardot B (1999) Comparing the effectiveness of radish cover crop, oilseed rape volunteers and oilseed rape residues incorporation for reducing nitrate leaching. Nutr Cycl Agroecosyst 55:207–220. doi:10.1023/A:1009870401779

Kage H (2000) Simulation modelling for improving nitrogen use efficiency in intensive cropping systems. Habilitationsschrift,

University of Hannover. http://deposit.ddb.de/cgi-bin/dokserv?idn=977957020
Kage H, Stützel H (1999) HUME: an object oriented component library for generic modular modelling of dynamic systems. In: Donatelli CSM, Villalobos F, Villar JM (eds) Modelling cropping systems, ESA conference, Lleida, June 1999. European Society of Agronomy, Lleida, p 299
Kage H, Alt C, Stützel H (2003) Aspects of nitrogen use efficiency of cauliflower I. A simulation modeling based analysis of nitrogen availability under field conditions. J Agric Sci Camb 141:1–16. doi:10.1017/S0021859603003344
Kage H, Kochler M, Stützel H (2004) Root growth and dry matter partitioning of cauliflower under drought stress conditions: measurement and simulation. Eur J Agron 20:379–394. doi:10.1016/S1161-0301(03)00061-3
Kersebaum KC (2007) Modelling nitrogen dynamics in soil-crop systems with HERMES. Nutr Cycl Agroecosyst 77:36–52. doi:10.1007/s10705-006-9044-8
Köhler K, Duynisveld WHM, Böttcher J (2006) Nitrogen fertilization and nitrate leaching into groundwater on arable sandy soil. J Plant Nutr Soil Sci 169:185–195. doi:10.1002/jpln.200521765
La Scala N, Lopesa A, Spokas K, Bolonhezia D, Archer DW, Reicosky DC (2008) Short-term temporal changes of soil carbon losses after tillage described by a first-order decay model. Soil Tillage Res 99:108–1108. doi:10.1016/j.still.2008.01.006
Lickfett T (1993) Auswirkungen verminderter Produktionsintensität in zwei Rapsfruchtfolgen auf Elemente des N-Haushalts im System Boden-Pflanze. Dissertation, University of Göttingen
Makowski D, Maltas A, Morison M, Reau R (2005) Calculating N fertilizer doses for oil-seed rape using plant and soil data. Agron Sustain Dev 25:159–161. doi:10.1051/agro:2004052
Malagoli P, Laine P, Rossato L et al (2005) Dynamics of nitrogen uptake and mobilization in field-grown winter oilseed rape (Brassica napus) from stem extension to harvest I. Global N flows between vegetative and reproductive tissues in relation to leaf fall and their residual N. Ann Bot (Lond) 95:853–861. doi:10.1093/aob/mci091
Marquardt DW (1963) An algorithm for least-squares estimation of nonlinear parameters. J Soc Ind Appl Math 11:431–441. doi:10.1137/0111030
Mary B, Beaudoin N, Justes E, Machet JM (1999) Calculation of nitrogen mineralization and leaching in fallow soil using a simple dynamic model. Eur J Soil Sci 50:549–566. doi:10.1046/j.1365-2389.1999.00264.x
Monteith JL (1973) Principles of environmental physics. Edward Arnold, London
Mueller T, Jensen LS, Magid J et al (1997) Temporal variation of C and N turnover in soil after oilseed rape straw incorporation in the field: simulations with the soil-plant-atmosphere model DAISY. Ecol modell 99:247–262
Nicolardot B, Recous S, Mary B (2001) Simulation of C and N mineralization during crop residue decomposition: a simple dynamic model based on the C:N ratio of the residues. Plant Soil 228:83–103. doi:10.1023/A:1004813801728
SAS Institute Inc (1989) SAS/STAT® user's guide, version 6, 4th edn, vol 2. SAS Institute, Cary, NC
Shepherd MA, Sylvester-Bradley R (1996) Effect of nitrogen fertilizer applied to winter oilseed rape (Brassica napus) on soil minerl nitrogen after harvest and on the response of a succeeding crop of winter wheat to nitrogen fertilizer. J Agric Sci Camb 126:63–74
Sieling K, Kage H (2006) N balance as an indicator of N leaching in an oilseed rape—winter wheat—winter barley rotation. Agric Ecosyst Environ 115:261–269. doi:10.1016/j.agee.2006.01.011
Sieling K, Günther-Borstel O, Teebken T et al (1999) Soil mineral N and N net mineralization during autumn and winter under an oilseed rape—winter wheat—winter barley rotation in different crop management systems. J Agric Sci Camb 132:127–137. doi:10.1017/S0021859698006273
Smith P, Smith JU, Powlson DS et al (1997) A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81:153–225. doi:10.1016/S0016-7061(97)00087-6
Stockle CO, Martin SA, Campbell GS (1994) CropSyst, a cropping systems simulation model: water/nitrogen budgets and crop yield. Agr Syst 46:335–359
Trinsoutrot I, Nicolardot B, Justes E et al (2000) Decomposition in the field of residues of oilseed rape grown at two levels of nitrogen fertilisation. Effects on the dynamics of soil mineral nitrogen between successive crops. Nutr Cycl Agroecosyst 56:125–137. doi:10.1023/A:1009838618133
Van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892–898
Van Genuchten MT, Leij FJ, Yates SR (1991) The RETC code for quantifying the hydraulic functions of unsaturated soils, version 1.0., rep. no. EPA report 600/2-91/065. U.S. Salinity Laboratory, USDA, ARS, Riverside
Verberne ELJ, Hassink J, De Willigen P, Groot JJR, van Veen JA (1990) Modelling organic matter dynamics in different soils. Neth J Agric Sci 38:221–238
Wösten JHM, Van Genuchten MT (1988) Using texture and other soil properties to predict the unsaturated soil hydraulic functions. Soil Sci Soc Am J 52:1762–1770