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RESEARCH ARTICLE

Nitrogen management in organic farming: comparison of crop rotation residual effects on yields, N leaching and soil conditions

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Abstract After 3 years of different crop rotations in an organic farming experiment on a sandy soil in northwest Germany, spring triticale was cultivated on all plots in the fourth year to investigate residual effects on yield, nitrogen (N) leaching and nutrient status in the soil. Previous crop rotations differed in the way N was supplied, either by farmyard manure (FYM, 100 and 200 kg N ha^{-1} year^{-1}) or by arable legumes like grass-red clover and field beans, or as a control with no N. Other crops in the rotations were maize, winter triticale and spring barley. Additional plots had a 3-year grass-clover ley, that was ploughed-in for spring triticale in the fourth year. Yields of spring triticale were moderate and largest for ploughed-in grassland leys and grass-red clover and plots that had previously received farmyard manure. The former crop rotation, including grassland break-up, had a significant effect on most yield and environmental parameters like residual soil mineral nitrogen (SMN) and N leaching and on the level of available K in the soil. The single crop harvested in the year before spring triticale had a significant effect on yield parameters of spring triticale, less so on SMN and N leaching in the fourth year and no effect on available nutrients (P, K, Mg) and pH in the soil. We conclude that the effects of arable legumes were rather short lived while ploughing of 3-year grassland leys had a profound influence on mineralization processes and subsequently on yield and N losses.

Keywords Crop rotation · Grass-clover · Grassland ploughing · N leaching · Organic farming

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Introduction

Organic farming relies heavily on nitrogen (N) fixation by legumes to supply arable crops with N (Berntsen et al. 2006). There are two main ways of supplying N to cash crops: firstly, by including arable legumes into the crop rotation and, secondly, by applying farmyard manure from feeding leguminous fodder to ruminants. One disadvantage of arable legumes is an unpredictable N efficiency as the N need of the following cash crop in time and amount is not always matched by the available N provided by the legume (Crews and

Peoples 2005). Farmyard manure, on the other hand, can be applied to the field before ploughing or before preparation of the seedbed and a second application as a top dressing to the standing crop is also possible. The amount of N provided to the following plant is thus better controlled. Ploughing in of legumes or grassland leys can also lead to a surplus of N in the soil that, if not used by the following crop, is prone to leaching during the following winter period in areas of high ground-water renewal and on sandy soils. Leaching of N can be substantial and reduces the efficient and lasting supply of N to cash crops in organic farming rotations. Thus strategies to improve N efficiency and good management practices are needed, especially on these light soils (Eriksen et al. 2008). Well established grass-clover fields that are mainly used for cutting and as a feed source for ruminants usually show small N leaching (Klempt 1997). Clover content in grass-clover fields can oscillate due to self-regulating mechanisms and imposition of various management schemes (Loiseau et al. 2001).

An experiment with different crop rotations including grass-clover leys and arable legumes was conducted on an organic farm with sandy soils in northwest Germany. The aim was to compare two ways of supplying N to cash crops, either by legumes on arable land or by grass-clover and farmyard manure and examine the effect on yields and impact on the environment. After three experimental years spring triticale was cultivated on all plots. In this paper we present the residual effects of the different crop rotations and the ploughing-in of the grass-ley on the yield of spring triticale, soil conditions and on environmental parameters like residual mineral soil N in autumn and N leaching after harvest.

Materials and methods

Experimental site, management and sampling

The experimental field (52°55′14″N and 8°14′35″E) is a part of the organic farm 'Bakenhus' which is located in the county of Oldenburg in northwest Germany. The landscape and soil were formed during the 'Elster' ice age and consist mainly of sandy glacial till. The soil can be described as a stagnic Cambisol (WRB) with a sand content of >82% in the topsoil and a relatively high clay content at 70–85 cm of >16%; total carbon content was 1.24% and total N 0.103% with a C:N ratio of 12:1. Before the start of the experiments the field had sufficient amounts of all macro nutrients in the topsoil.

Since 1996 the management of the farm followed the principles of organic farming. The previous experimental split-plot design consisted of three blocks (replicates), each with six whole-plots and each whole-plot with 3 sub-plots of 162 m^2, making a total of 54 plots. The six crop rotation treatments (CRT) were assigned to the whole-plots. CRT can be seen as a combination of crop rotations and different N supply including a 3-year grass-clover ley (see Table 1). In the

Table 1 The previous crop rotation experiment (2003–2005) and the cultivation of spring triticale in 2006 to test residual effects of crop rotation treatments

2003–2005		2006	Notes
Crop rotation treatment (CRT)	Crops		Crops cultivated parallel each year (3 sub-plots in whole-plot) and in rotation on each sub-plot in 3 years
FYM 100	MA, TR, SB	Spring TR	100 kg N ha^{-1} $year^{-1}$ by FYM
FYM 200	MA, TR, SB	Spring TR	200 kg N ha^{-1} $year^{-1}$ by FYM
Grass-red clover	GC, SB, TR	Spring TR	N input by 1-year grass-red clover (GC)
Field bean	FB, TR, SB	Spring TR	N input by field bean (FB)
Control N0	MA, TR, SB	Spring TR	No N provided
Grassland ley	G0, G+, G++	Spring TR	3-year grassland with white clover (G+, G++)

Treatments/crop rotations allocated to 6 whole-plots with 3 sub-plots (3 crops parallel); 3 blocks (replicates)

FYM farm yard manure; Crops: *TR* winter triticale; *SB* spring barley; *MA* maize; *GC* grass-red clover (30–40% clover in late summer); *FB* field bean; *G0, G+, G++* 3-year grassland ley based on ryegrass with 0–5, 30 and 50% white clover, respectively; 3 replications; 4 suction cups per plot; plot size 162 m^2

3 sub-plots in each whole-plot the 3 crops of every CRT were cultivated parallel in each year (Table 1). The 3-year grassland ley was based on a ryegrass (*Lolium perenne*) dominated mixture on three adjacent plots which had either no clover (0–5%) or proportions of 30% and 50% of white clover on average. These plots were only ploughed-in after the third year before the cultivation of spring triticale in the fourth year. The grass-red clover plots were part of an arable rotation and ploughed after 1 year. In the grass-red clover plots the sward consisted of Italian ryegrass with on average 35% red clover in late summer. To allow modelling of the crop effects, no catch crops were sown following harvest of grain or maize. The previous experiment was run for 3 years (2003–2005/06) and after that spring triticale was sown on all plots in 2006 to assess residual effects. About 5 t ha^{-1} of horse manure was applied in spring 2006 and all plots, including the grasslands, were ploughed. Total nitrogen provided by the horse manure was approximately 25 kg N ha^{-1}. Harvest of triticale was in early August 2006 and straw was left on the field; after stubble cultivation a catch crop mixture based on pea and vetch was sown to serve as a ground cover over winter. Soil samples (0–30 cm) were taken in late summer after harvest and residual soil mineral nitrogen (0–90 cm) sampled in early November.

Four ceramic suction cups (P 80) per plot installed at 70 cm depth were used to collect water samples. Each cup was sampled separately after every 1 or 2 weeks during the leaching period. A permanent suction of 0.3–0.4 bar was applied by a pressure-controlled vacuum pump. During the main water leaching period from the middle of October to April, samples were taken fortnightly and analyzed for nitrate concentration. Aliquot samples from 4 suction cups per plot were pooled. The nitrate concentration was determined photometrically with an EPOS 5060 auto-analyzer (Eppendorf). The nitrate leaching losses were calculated as the product of the nitrate concentration and the amount of water percolating through the profile during a given time. It was assumed that after the soil water content had reached field capacity in autumn, daily drainage equalled rainfall minus evapotranspiration (Haude; DVWK 1996). The Haude method to determine the potential evapotranspiration includes measurements of relative air humidity, air temperature and a monthly coefficient for crop and plant cover. On a monthly basis this approach gives good estimates comparable to those of much more complicated methods. During winter, rainfall is the main effect on the amount of water leached, while the importance of evapotranspiration is much less compared to spring and summer. It can be assumed that in winter values for potential and actual evapotranspiration are very close. The sum of nitrate leaching for all sample dates while percolation occurred, gave a total loss over winter. The date for leaching to start was inferred from soil and meteorological data and adjusted by other sources of information from other sites (lysimeter). Permanent leaching commenced around November 1 and sampling ended in April 2007. Possible differences in soil moisture between the plots due to previous management were not considered. The German Weather Service (DWD) provided climatic data from a station that is located about 1 km from the experimental site. The experimental year 2006/07 was relatively warm (11.8°C); and while rainfall of 810 mm was average, the calculated amount of water leached of 342 mm was about 40 mm above long-term average.

In addition, the soil mineral nitrogen content (NO_3–N + NH_4–N; SMN) was determined at the start and the end of the leaching period. Soil samples were taken from three depths: 0–30, 30–60, and 60–90 cm. Farmyard manure (FYM) was produced by an Aberdeen Angus suckler cow herd on the organic farm 'Bakenhus'. For maize and summer-barley, FYM was spread after ploughing and before sowing of the crops in one application. Winter-triticale, on the other hand, received two applications, one in autumn before sowing and a second in spring on top of the crops.

Chemical analyses

The pH in soil samples was determined in a 0.01 M $CaCl_2$ solution. Total carbon (TC) was determined by burning the sample in a pure O_2-atmosphere at 950°C and measuring the resulting CO_2 concentration by means of an infrared-cell in a LECO SC 444 analyzer (Leco Ltd). For the non-calcareous sandy soils in this experiment the total organic carbon content (TOC) might be taken as equal to the total carbon content (TC). All total nitrogen contents (TN) in soil and plant material were determined through the automated macro N (Heraeus) following an altered method of Dumas.

For the determination of soil mineral nitrogen (SMN), NO_3 and NH_4 were extracted from a 150 g soil sample by shaking for 1 h with 600 ml of 0.0125 M l^{-1} $CaCl_2$. Filtered extracts were analyzed for NO_3–N and NH_4–N photometrically with an EPOS 5060 auto-analyzer. Soil solution NO_3–N concentrations and exchangeable NH_4–N were calculated from the concentration and volume of the extract, the mass of soil extracted and the soil moisture content.

Potassium (K) and phosphorus (P) were extracted from soil samples following the CAL-method (calcium-acetate-lactate extract) and magnesium (Mg) extracted by $CaCl_2$ as described in Hoffmann (1991). The filtered extracts were analyzed for PO_4^{3-}–P with the EPOS 5060 auto-analyzer and for K and Mg at the AAS (Varian SpectrAA300).

All plant materials were oven dried at 60°C as soon as possible after sampling. The dried and ground material (<1 mm) was analysed for dry matter content (DM) at 105°C and for TN directly.

All leaching water samples were filtered through N free paper filters on the day of sampling, stored at 4°C and analysed within 2 days. NH_4–N, NO_2–N, and NO_3–N were determined photometrically with an EPOS 5060 auto-analyzer, on the basis of a modified Berthelot-reaction (indophenolblue), a modified Griess-reaction, and a reduction with hydrazin followed by a modified Griess-reaction, respectively.

Statistical analysis

Statistical analyses were carried out using the software package Genstat (Payne 2002). In the split-plot design of the experiment crop rotation treatments (CRT) were assigned as whole-plots to the blocks and crops to the 3 sub-plots within the whole-plots. The full model is not completely orthogonal and is unbalanced as not all crop rotations include the same crops. We therefore did the data analysis in two steps. Firstly, we tested the effect of the crop rotation treatments by a one-way Analysis of Variance (ANOVA) at the whole-plot level and averaging over the three crops. This seemed justified as we were mainly interested in an accumulated effect of the crop rotations on the follow-up crop, spring triticale. Residuals were used to check the validity of the models. Predicted means are presented with least significant differences (LSD). To account also for the effect of the last single crop within the rotations before cultivation of spring triticale, we applied Linear Mixed Models (REML, restricted maximum likelihood) which gives Wald statistics. The importance of individual terms in the model can be assessed formally using the Wald statistic. The Wald statistics would have an exact χ^2 distribution, if the variance parameters were known, but because they must be estimated the statistic is only asymptotically distributed a χ^2 (Webster and Payne 2002). Using the χ^2 probabilities tends to give significant results rather too frequently. Some caution is needed for interpretation, especially when the value is close to a critical value (Webster and Payne 2002). A direct comparison of means is limited within the REML approach, but standard errors of differences of the predicted means (SED) are presented in the tables. Least significant differences can approximately be derived by 2*SED (Andrist-Rangel et al. 2007). With REML, the means are calculated from a linear transformation of the estimated parameter values, taking no account of the frequency counts for different factor combinations. Therefore, these predicted means will correspond to the averages over the factor combinations only with orthogonal data. In other cases, tables of means can be thought of as mean effects of factor levels adjusted for the mean values of any covariates and for any lack of balance in other factors: that is, as the means you would have expected if the data had been orthogonal (Payne 2002).

Results

Effects of the crop rotations

The different crop rotation treatments resulted in differences in yields, especially for grain (Table 2). While ploughing-in of grassland ley plots led to the highest yields and N concentrations in grain and straw of follow-up spring triticale, the plots that received farmyard manure or had 1-year grass-red clover as a N source in the rotation showed intermediate results, while the field bean rotation and N0 (Control) rotation led to the weakest performance. The leguminous plant field bean did not provide surplus N at the right time and in the amount for this crop rotation to have an effect on yield parameters of the follow-up spring triticale. This could have been caused by a limited N fixing of the field beans or a different pattern of N mineralization.

Table 2 Results of the analysis of variance (ANOVA, *P*-values) and means for some plant (harvest) parameters for the different crop rotation treatments

Crop rotation treatment (CRT)	DM yield grain (kg ha^{-1})	N yield grain (kg ha^{-1})	N content grain (%)	DM yield straw (kg ha^{-1})	N yield straw (kg ha^{-1})	N content straw (%)
ANOVA	$P < 0.008$	$P < 0.001$	$P < 0.001$	$P < 0.051$	$P < 0.011$	$P < 0.078$
FYM 100	2,457	41.5	1.70	1,572	8.7	0.55
FYM 200	2,245	39.4	1.75	1,643	9.4	0.57
Grass-red clover	2,287	40.5	1.74	1,147	5.2	0.45
Field bean	1,710	28.8	1.70	1,395	8.0	0.56
Control N0	1,918	31.3	1.65	1,514	7.9	0.50
Grassland ley	2,914	64.6	2.21	1,891	11.1	0.60
LSD[a]	541	8.0	0.12	431	2.6	0.10

[a] *LSD* least significant differences ($P < 0.05$); *DM* dry matter

The N provided by ploughing of 3-year grassland leys could not be fully utilized by spring triticale and resulted in the highest residual soil mineral nitrogen (SMN) in autumn after harvest and correspondingly high calculated nitrogen leaching (Table 3). Differences in N leaching were more pronounced than in SMN and the rotation that received 100 kg N in farmyard manure (FYM 100) had similar N leaching as compared to the ploughed-in grassland plots. Average NO_3–N concentrations in leached water ranged from 19.6 mg l^{-1} for the control plots to 34.7 mg l^{-1} for the former grassland plots. The course of NO_3–N concentrations showed two peaks, one in early December and a second in mid January. Generally, nitrate concentrations were relatively high and had been so during the last 2 years of the initial experiment as well: on average 20 mg l^{-1} for crop rotations, except for the 3-year grassland leys which had concentrations as low as 3–5 mg l^{-1}. Differences in N leaching between FYM 100 and 200 can partly be explained by the coincidence of peak nitrate concentrations with the time of largest leaching for FYM 100; which was not the case for FYM 200.

More than 3 years of different management did not lead to distinctive differences in available P (CAL) and Mg concentrations in the topsoil; differences in pH were negligible. Potassium, however, reacted rapidly to the large offtake with harvested material when no K was applied. Only rotations that received farmyard manure in a range of 15–30 t ha^{-1} each year had a substantial return and input of K.

Effects of the crop rotations and the last crop before triticale

Similar to the ANOVA results, the probabilities for the Wald statistic in the REML analysis indicate significance of treatment effects (Table 4). The model here is

Table 3 Results of the analysis of variance (ANOVA, *P*-values) and predicted means for some environment and soil parameters for the different crop rotation treatments

Crop rotation treatment (CRT)	SMN (kg ha^{-1})	N leaching[2] (kg ha^{-1})	P soil (mg kg^{-1})	K soil (mg kg^{-1})	Mg soil (mg kg^{-1})	pH soil
ANOVA	$P < 0.001$	$P < 0.001$	$P < 0.111$	$P < 0.001$	$P < 0.063$	$P < 0.091$
FYM 100	64.2	105.5	62.2	101.9	35.8	5.1
FYM 200	57.9	85.2	65.3	113.8	34.2	4.9
Grass-red clover	61.4	82.5	58.2	47.0	29.1	4.9
Field bean	58.4	80.9	56.7	50.8	26.0	4.8
Control N0	55.9	66.9	60.1	44.8	26.2	4.8
Grassland ley	94.7	121.2	56.6	38.4	28.7	4.8
LSD[a]	14.6	19.4	7.0	21.9	7.4	0.2

[a] *LSD* least significant differences ($P < 0.05$); [2]N leaching = NO_3–N; *SMN* residual soil mineral N (0–90 cm, NO_3–N + NH_4–N)

Table 4 The chi-square probabilities for the Wald statistic (REML) of the effects of crop rotation treatment (CRT) and the last crop harvested before cultivation of triticale on plant parameters and on environmental and soil parameters

	DM yield grain	N yield grain	N content grain	DM yield straw	N yield straw	N content straw
Crop rotation treatment (CRT)	<0.001	<0.001	<0.001	0.005	<0.001	0.049
Last crop (LC)	<0.001	<0.001	<0.001	0.596	0.018	<0.001
CRT × LC	0.021	0.357	0.815	0.971	0.728	0.378
	SMN	N leaching	P soil	K soil	Mg soil	pH soil
Crop rotation treatment (CRT)	<0.001	<0.001	0.034	<0.001	0.009	0.022
Last crop (LC)	0.067	0.981	0.757	0.408	0.371	0.291
CRT × LC	0.838	0.635	0.263	0.615	0.139	0.270

DM yield dry matter yield; *SMN* residual soil mineral N (0–90 cm, NO_3–N + NH_4–N)

extended to include the last crop before the cultivation of spring triticale in 2006. It is most striking that the last crop had a significant effect on most yield-related parameters of spring triticale, but not on SMN, N leaching and concentrations of macronutrients. This indicates that effects of single crops were already levelled out by the yield response of spring triticale and that surplus N and K dynamics were actually influenced by differences in management, that is, application of farmyard manure and ploughing-in of grassland leys.

Tables 5, 6, 7 present predicted means from the REML analysis for N yield and environmental parameters and reveal some interesting effects of single last crops on follow-up spring triticale. The tables give means for N yields of spring triticale and SMN and N leaching in the following autumn and winter for plots of former different crop rotations and the last crop cultivated before sowing of spring triticale. Field bean as a legume plant had no effect on grain N yield of spring triticale while 1-year grass-red clover provided enough N for the triticale to yield as much as ploughing-in of 3-year grassland leys and application of farmyard manure. The SMN and N leaching after harvest of spring triticale on the plots of the former 1-year grass-red clover, on the other hand, were much less than on the former 3-year grassland ley and even less than on the FYM plots. The proportion of red clover in the 1-year leys was about 30% in late summer 2005, while the proportion of white clover averaged around 50% for the same time period in the 3-year grassland plots with clover. The different contents of white clover in the grassland plots had only a minor effect on grain yield of the follow-up spring triticale and subsequent N leaching. But larger proportions of white clover resulted in increased grain N concentrations of spring triticale and larger SMN in autumn. Spring barley as a last crop resulted in lower dry matter and N grain yields of spring triticale compared to winter-triticale and maize as last crops, while differences between these last crops for SMN and N leaching were relatively small.

Discussion

The design of crop rotations must ensure soil fertility for maintaining productivity and prevent problems with weeds, pests and diseases; the crop rotation is thus one of the building blocks of organic farming systems (Olesen 1999). One of the main rotational effects is increased N supply especially to cash crops and forage; the ratio of N fixing crops and arable cash crops has a major impact on agronomic success and the environment (Watson et al. 1999).

The grain yields of spring triticale in our experiments, cultivated after 3 years of different crop rotations, ranged from 1.6 t ha^{-1} following spring barley in the field bean rotation to 3.1 t ha^{-1} after ploughing-in of grassland with 50% of white clover. Dry matter yields for spring triticale on the 'Bakenhus' farm were up to 3.0 t ha^{-1}, which was a satisfactory yield on these sandy soils (G. Wolters, farm manager; personal communication). Generally, yields were affected by weather conditions in early spring and summer. During spring, plant development was hampered by cold and wet weather and maturity was

Table 5 Predicted means of grain N yield (kg ha^{-1}) of spring triticale as an effect of different crop rotation treatments (CRT) and the last crop (LC) before cultivation of spring triticale

Crop rotation treatment (CRT)	Last crop (LC)							
	TR (kg ha^{-1})	SB (kg ha^{-1})	MA (kg ha^{-1})	GC (kg ha^{-1})	FB (kg ha^{-1})	G0 (kg ha^{-1})	G + (kg ha^{-1})	G ++ (kg ha^{-1})
FYM 100	47.6	34.7	42.3	–	–	–	–	–
FYM 200	44.6	30.8	42.7	–	–	–		–
Grass-red clover	34.8	30.3	–	56.5	–	–	–	–
Field bean	30.6	26.9	–	–	29.1	–	–	–
Control N0	35.3	27.9	30.7	–	–	–	–	–
Grassland ley	–	–	–	–	–	56.5	67.9	69.5

SED		(For the same level of CRT)	(For the same level of LC)
Average	4.80	4.09	4.89
Maximum	4.89	4.09	4.89
Minimum	4.09	4.09	4.89
AVD	23.08		

Crops: *TR* winter triticale; *SB* spring barley; *MA* maize; *GC* grass-red clover (30–40% clover in late summer); *FB* field bean; *G0, G+, G++* 3-year grassland ley with 0–5, 30 and 50% white clover, respectively; *SED* standard error of differences of the mean; least significant difference would approximately be 2 * SED; *AVD* average variance of differences

Table 6 Predicted means of residual SMN in autumn (kg ha^{-1}) after spring triticale as an effect of different crop rotations (CR) and the last crop (LC) before cultivation of spring triticale

Crop rotation treatment (CRT)	Last crop (LC)							
	TR (kg ha^{-1})	SB (kg ha^{-1})	MA (kg ha^{-1})	GC (kg ha^{-1})	FB (kg ha^{-1})	G0 (kg ha^{-1})	G + (kg ha^{-1})	G ++ (kg ha^{-1})
FYM 100	70.2	62.3	60.1	–	–	–	–	–
FYM 200	58.8	49.9	65.0	–	–	–	–	–
Grass-red clover	51.0	55.4	–	77.7	–	–	–	–
Field bean	56.1	58.6	–	–	60.5	–	–	–
Control N0	58.8	52.6	56.2	–	–	–	–	–
Grassland ley	–	–	–	–	–	83.1	93.6	107.4

SED		(For the same level of CRT)	(For the same level of LC)
Average	11.21	11.15	11.22
Maximum	11.22	11.15	11.22
Minimum	11.15	11.15	11.22
AVD	125.7		

Crops: *TR* winter triticale; *SB* spring barley; *MA* maize; *GC* grass-red clover (30–40% clover in late summer); *FB* field bean; *G0, G+, G++* 3-year grassland ley with 0-5, 30 and 50% white clover, respectively; *SED* standard error of differences of the mean; least significant difference would approximately be 2 * SED; *AVD* average variance of differences

enhanced by hot and dry conditions in June and July 2006. Nitrogen transformation in soil and N uptake by plants might not have been optimal.

The control plots had received no N during the last 3 years apart from atmospheric deposition, mineralization and a rather moderate application of horse

Table 7 Predicted means of NO_3-N leaching (kg ha^{-1}) in winter after spring triticale as an effect of different crop rotations (CR) and the last crop (LC) before cultivation of spring triticale

Crop rotation treatment (CRT)	Last crop (LC)							
	TR (kg ha^{-1})	SB (kg ha^{-1})	MA (kg ha^{-1})	GC (kg ha^{-1})	FB (kg ha^{-1})	G0 (kg ha^{-1})	G + (kg ha^{-1})	G ++ (kg ha^{-1})
FYM 100	106.0	105.3	105.2	–	–	–	–	–
FYM 200	93.1	77.6	89.4	–	–	–	–	–
Grass-red clover	74.0	90.3	–	83.1	–	–	–	–
Field bean	84.4	79.8	–	–	78.3	–	–	–
Control N0	63.6	69.2	67.9	–	–	–	–	–
Grassland ley	–	–	–	–	–	122.4	115.3	126.0

SED		(For the same level of CRT)	(For the same level of LC)
Average	12.64	11.68	12.73
Maximum	14.07	13.10	14.07
Minimum	11.51	11.51	12.60
AVD	160.0	136.8	162.2

Crops: *TR* winter triticale; *SB* spring barley; *MA* maize; *GC* grass-red clover (30–40% clover in late summer); *FB* field bean; *G0, G+, G++* 3-year grassland ley with 0–5, 30 and 50% white clover, respectively; *SED* standard error of differences of the mean; least significant difference would approximately be 2 * SED; *AVD* average variance of differences; one missing data

manure before cultivation of spring triticale of about 25 kg total N ha^{-1}. The residual soil mineral nitrogen and leaching losses resulting from these soil and weather related processes were, in proportion to the other treatments, relatively high. This indicates that during the dry period in June and July 2006 N mineralization and N uptake in plants were reduced and after rewetting of the soil in August strong mineralization set in, leading to large residual soil mineral nitrogen. The mineralization of accumulated organic matter in the ploughed grassland leys and grass-clover plots and in the farmyard manure plots would have added to these effects.

The year 2006/07 was relatively warm with larger leaching than average. A markedly mild period in mid-winter was accompanied by relative high rainfall and showed translocation of large amounts of nitrate. The N leached during this period was possibly not only residual but also from actual mineralization processes. Mineralization processes are influenced profoundly by temperature and temperature changes with a lower limit close to freezing. The majority of soil micro-organisms are mesophyllic and prefer moderate temperatures (optimum activity between 25 and 37°C) and a base temperature of 5°C. Freezing/thawing changes may have comparable effects to those of wetting/drying and result in the release of soluble materials and/or disruption of soil aggregates (Jarvis et al. 1996). Franko (1984) and Gill et al. (1995) confirm that mineralization can provide quite substantial N at low temperatures. During two weeks in mid January daily temperatures were on average 8.5°C (5.6–13.2°C) and rainfall amounted to 100 mm of which 45 mm occurred within 3 days. The N leaching losses during that period accounted for 33% of the total N losses during the winter of 2006/07. This could help to explain further why N leaching losses were larger than the SMN in the previous autumn. Usually calculated N leaching is positively related to SMN at the end of the growing season and often amounts to 40–60% of the SMN depending on management and weather conditions (Kayser 2003; Wachendorf et al. 2006). In our experiments, the proportion of N leaching to SMN turned out to be on average 120% for the control plots, 147% for FYM 200 (164% for FYM 100), 139% for the field bean plots, 127% for the 3-year grassland plots, and 107% for grass-red clover. Similar relationships were also reported by Kayser et al. (2008) when permanent grassland was ploughed for arable use; after a relatively dry summer, they found N leaching in winter to be 135% of SMN in the first year and 95% in the second year. This indicates that the 'normal' relation between SMN and N leaching can be overruled by extreme weather conditions and strong mineralization in late summer and/or ongoing mineralization in winter. The explanation of such phenomena is also sensitive to technical aspects, as data from one point in time (SMN) are compared with a more continuous measurement like nitrate leaching by ceramic cups and permanent suction. Berntsen et al. (2006) report findings from ploughing of a 3-year-old grass-clover sward on sand and loamy sand soils in Denmark followed by spring barley. While N leaching was moderate during the pasture time (9–64 kg N ha^{-1}), they found larger N leaching losses after ploughing which amounted to 63–216 kg N ha^{-1} in the first year and 61–235 kg N ha^{-1} in the second year. Estimations and modelling of the organic matter turnover should include an intermediate pool with a half-life of 2–3 years (Berntsen et al. 2006). The authors further conclude that careful management is required to handle and limit nitrate leaching after ploughing of grassland and grass-clover even in low input systems. Similar conclusions have been drawn by Kayser et al. (2008) from the break-up of permanent grassland on sandy soils in northwest Germany under conventional farming conditions. Leaching losses after spring barley + catch crop (yellow mustard) and maize without and with N fertilizer cultivated after ploughing of permanent grassland were 45–81 kg N ha^{-1} for barley and 118–216 kg N ha^{-1} for silage maize in the first year and 33–134 kg N ha^{-1} after silage maize in the second year (Kayser et al. 2008). Corresponding peak nitrate concentrations were as high as 120 mg NO_3–N l^{-1} for N fertilized barley and >200 mg NO_3–N l^{-1} for silage maize. However, the highest concentrations when no N was applied reached 40–60 mg. This is in the range of the 55 mg NO_3–N l^{-1} found after ploughing of 3-year-old grassland in our experiment. After harvest of spring triticale a catch crop mixture of pea and vetch was planted relatively late in September, providing at least plant cover during winter. N uptake by this catch crop might be roughly estimated to have been 10–15 kg N ha^{-1}. Eriksen et al. (2008) report substantial reduction in N leaching after ploughing of grassland and cultivation of spring barley with under-sown ryegrass and the use of catch crops on sandy soils is seen as one of the most effective measures to control nitrate leaching (Köhler et al. 2006; Eriksen et al. 2008). In our initial experiment, nitrate concentrations were reduced below 1-year grass-red clover plots to 6–7 and to 4 mg l^{-1} below 3-year grassland during winter compared to 12–27 mg l^{-1} under arable plots. This demonstrates the potential of catch crops, and especially grasslands, in reducing N leaching, but it also shows the potential for N mineralization of some arable fields even under reduced N input conditions (Köhler et al. 2006).

There is a wide range in the amount of N fixed by legumes and supplied to the following crop. In a 3-year field experiment at four sites in northwest Germany peas were found to have an average amount of N_2 fixation of 141 kg N ha^{-1} $year^{-1}$ (18–335 kg N ha^{-1}) while corresponding values for field beans amounted to 193 kg N ha^{-1} $year^{-1}$ (18–380 kg N ha^{-1}) (Jost 2003). For grass-clover swards with no N fertilizer and under different climatic conditions and with different proportions of clover values of 99–231 kg N (Ledgard 2001; Ledgard et al. 1999), 0–50 kg N (Hack-ten-Broeke and de Groot 1998) and 57–166 kg N ha^{-1} $year^{-1}$ for N fixation have been reported. The proportion of N stored in roots and stubble of the grass-clover swards is substantial (Høgh-Jensen and Schjoerring 2001; Berntsen et al. 2006). When grassland or grass-clover is ploughed-in, the amount and timing of N from mineralization processes is, among others, dependent on the age of the sward, season of break-up, proportion of clover in the sward, and the previous N fertilization and management (Hack-ten-Broeke and de Groot 1998; Aarts et al. 2000; Berntsen et al. 2006). Also, the ploughing of field bean stubble and plant residue is supposed to be a good N source for the following crop. However, as the residues are easily decomposed the released N might only be stored over a longer period of time to supply the crops in the next season by a good catch crop. Incorporating the stubble of grain crops will, if at all, only provide little N, especially if the previous crop did not receive organic manure or was not a legume (Bachinger and Zander 2003).

The effect of the proportion of white clover in ploughed-in 3-year grassland leys on following grain yield in our experiments was generally small and considerable only when the proportion of clover was >50%. This tendency was stronger for grain N yield and SMN in autumn, but not for N leaching losses. However, statistical evidence was poor. Yield of spring triticale from plots that had received farmyard manure before was only second to ploughed grassland, while SMN in the FYM plots was much smaller than from the previous grassland. On the other hand, N leaching losses for FYM 100 were similar to the ploughed grassland plots, while losses from FYM 200 were significantly smaller. The small differences between former FYM 100 and FYM 200 in DM yield of spring triticale indicate that the larger input could not be utilized. The practice of applying 50% of FYM as a top dressing to winter triticale and to 100% after ploughing for spring-sown crops with only shallow incorporation in the previous years could have promoted gaseous losses and limited the N effect. When 1-year grass-red clover plots were ploughed, yields of spring triticale were almost level with yields obtained after break up of the 3-year grassland. However, SMN was on average 17 kg N ha^{-1} less and N leaching losses were smaller by 38 kg N ha^{-1}. This suggests that plant residues and N from red clover in the 1-year leys were sufficient for providing the spring triticale with N but did not cause over fertilization like the ploughing-in of the 3-year grass and grass-clover swards. Askegaard and Eriksen (2007) found legume catch crops a valuable N source for grain production on a coarse sandy soil and reported fertilizer-replacement values in a following unfertilized spring barley to correspond to 120 and 103 kg N ha^{-1} for white and red clover, respectively. Furthermore, the effect of 1-year grass-red clover leys in our experiment seemed to be rather short lived as grass-clover leys that had been ploughed-in during the previous season did not show any effect on yield or N losses of spring triticale (see the triticale plots in the grass-red clover rotation). The proportion of red clover in late summer was about 40% in 2004 and 30% in 2005, the last year before cultivation of spring barley. These effects indicate that 3-year grassland leys differed from 1-year grass-red clover swards in management and resulting soil conditions. The residual effects of grass-red clover leys might thus be easier to predict from yield, N balance and proportion of clover while the situation becomes more complex with grassland ley swards that are >3 years. The effects might be much stronger for much older grassland. Eriksen et al. (2008) state that management strategies adopted in both the grassland and arable phases appear to be the primary instrument in avoiding nutrient losses in mixed crop rotations, irrespective of the grass proportion.

Potassium is a very dynamic nutrient in sandy soils (Kayser and Isselstein 2005). In our experiments only the supply of farmyard manure kept the level of available K constant over the period of more than 3 years. Especially the high offtake of K with harvested material in the 3-year grassland and grass-clover plots led to a significant reduction of available K to 35% of the K concentration in the former FYM plots. The concentrations were not yet low enough to have affected the yield of spring triticale, though. The concentrations of Mg were less or, as with P, hardly affected by the different management. These findings stress the importance of a balanced nutrient management, especially of K on coarse textured soils, to maintain soil fertility (Öborn et al. 2005). Sandy soils are in the long-term completely dependent on K input (Holmqvist et al. 2003).

Conclusions

We conclude that different crop rotations run for 3 years had a significant impact on the follow-up crop spring triticale. The positive effects of arable legumes including 1-year grass-red clover leys were rather short lived while break-up of 3-year grassland with and without white clover had a profound influence on mineralization processes and subsequently on yield and N losses of spring triticale. Weather conditions seemed to play a crucial role in determining the extent of mineralization, the timing of N supply, the uptake by crops and finally the amount of residual N. The proportion of clover adds to the variable range of N supply and possible N surplus. Without catch crops and an adjusted N fertilization it seems to be difficult to control N supply from grassland leys. On sandy soils the return of potassium deserves attention, especially after high offtake of nutrients with high yielding forages like grassland and grass-clover leys.

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