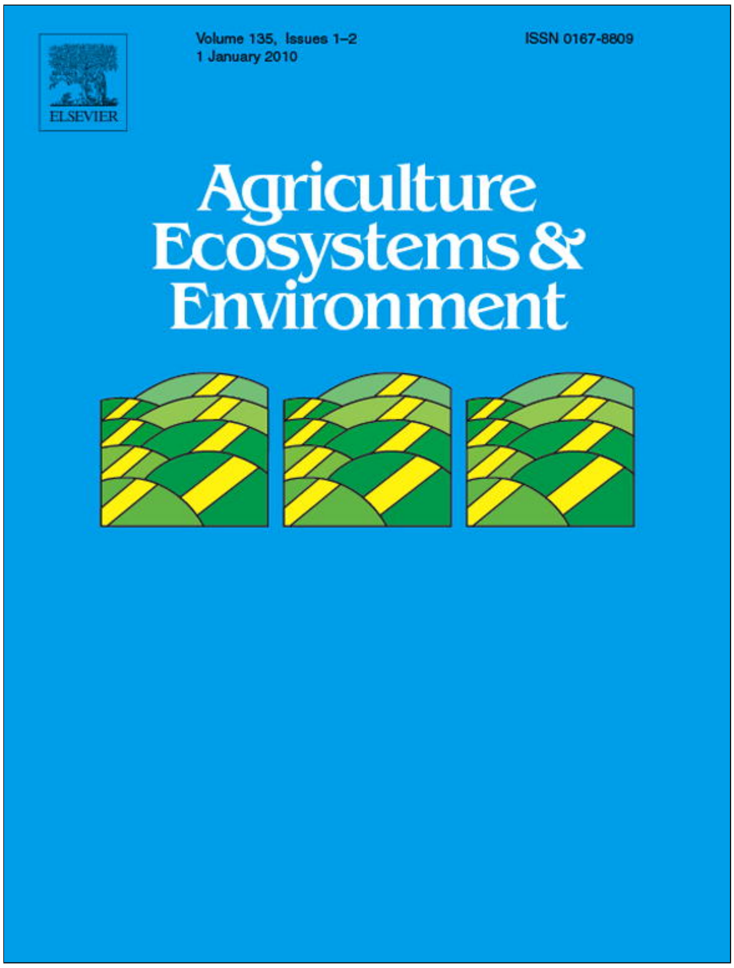
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Modelling nitrogen cycles of farming systems as basis of site- and farm-specific nitrogen management

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ABSTRACT

The paper describes a model designed for analysing interrelated nitrogen (N) fluxes in farming systems. It combines the partial N balance, farm gate balance, barn balance and soil surface balance, in order to analyse all relevant N fluxes between the subsystems soil–plant–animal–environment and to reflect conclusive and consistent management systems. Such a system approach allows identifying the causes of varying N surplus and N utilisation.

The REPRO model has been applied in the experimental farm Scheyern in southern Germany, which had been subdivided into an organic (org) and a conventional (con) farming system in 1992. Detailed series of long-term measuring data are available for the experimental farm, which have been used for evaluating the software for its efficiency and applicability under very different management, yet nearly equal site conditions.

The organic farm is multi-structured with a legume-based crop rotation (N_2 fixation: 83 kg ha^{-1} yr^{-1}). The livestock density is 1.4 LSU ha^{-1}. The farm is oriented on closed mass cycles.

The conventional farm is a simple-structured cash crop system based on mineral N (N input 145 kg ha^{-1} yr^{-1}). Averaging the years 1999–2002, the organic crop rotation reached, with regard to the harvested products, about 81% (6.9 Mg ha^{-1} yr^{-1}) of the DM yield and about 93% (140 kg ha^{-1} yr^{-1}) of the N removal of the conventional rotation. Related to the cropped area, the N surplus calculated for the organic rotation was 38 kg ha^{-1} yr^{-1} versus 44 kg ha^{-1} yr^{-1} for the conventional rotation. The N utilisation reached 0.77 (org) and 0.79 (con), respectively. The different structure of the farms favoured an enhancement of the soil organic nitrogen stock (35 kg ha^{-1} yr^{-1}) in the organic crop rotation and caused a decline in the conventional system (−24 kg ha^{-1} yr^{-1}). Taking account of these changes, which were substantiated by measurements, N surplus in the organic rotation decreased to 3 kg ha^{-1} yr^{-1}, while it increased to 68 kg ha^{-1} yr^{-1} in the conventional system. The adjusted N utilisation value amounted to 0.98 (org) and 0.69 (con), respectively.

1. Introduction

The intensification of agriculture has led to considerable yield increases, but also induced several environmental problems (Tilman et al., 2001). Many of them like the nitrate load of ground water, emissions of ammonia and greenhouse gases into the atmosphere and the eutrophication of ecosystems are related to high nitrogen (N) inputs in farming systems. Objections have been raised to insufficient N utilisation in agriculture and excessive N emissions from the viewpoint of environmental protection (Isermann, 1990; Van der Ploeg et al., 1997; Crutzen et al., 2008). Numerous measures and mitigation strategies were recommended, however, without adequate success (Isermann, 1994; Eichler and Schulz, 1998).

In crop production, N input is one of the most important yield enhancing factors, but also has an enormous relevance for the environment. Especially in N intensive farming systems the spatial and temporal optimisation of N fertilisation is difficult. Despite the latest application equipment and scientifically based fertilisation algorithms, N utilisation by crop production is incomplete; mainly under unfavourable weather conditions large amounts of the applied N cannot be used by the plants. These N quantities might be stored in the soil organic nitrogen stock (SON) or are subject to gaseous or leaching loss processes. In Germany, the N surplus and N utilisation by soil surface balance are currently 84 kg N ha^{-1} yr^{-1} and 48%; at farm gate scale 102 kg N ha^{-1} yr^{-1} and 38%, respectively (Osterburg, 2008).

In animal husbandry, N utilisation reaches only 10% in cattle fattening and up to 35% in dairy farming. The excreta contain 65–

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90% of the N supplied with the feed. Therefore, it is necessary to recycle these N quantities with losses as low as possible. Here, the often practised separation between crop production and animal husbandry is counterproductive. In regions with intensive stock keeping (above 2 LSU ha^{-1}) strained N fluxes with high N losses may occur.

Completely different is the situation in low-input systems like organic farming. Here, nitrogen often is a yield limiting factor. Negative N balances are recorded when the N outputs with cash crops exceed the N inputs from symbiotic N_2 fixation and organic fertiliser, thus reducing the SON stock. Additionally, N cycles in organic farming systems may be intensified by the use of biogas plants or intensive animal husbandry.

The examples show the great necessity of optimising the N cycles in farming systems. In the past, legal restrictions could not sufficiently reduce N emissions. Further success will only be possible by active participation of the farmers. Rising fertiliser prices will orient the farmers' economic interest towards an improvement of N efficiency. But also the growing awareness of the environment favours a critical rethinking of farm-specific N management.

This leads to the question of which management tools are suited for optimising N cycles. The most frequently used method for analysing farming systems is N balancing (Schröder et al., 2003). The calculated N surplus levels reflect the loss potential of reactive N compounds approximately (Oenema et al., 2003). In simple input-output accounting systems farms are regarded as "black box", where only inputs and outputs at the farm gate are quantified. These tools neglect internal farm structures, nutrient fluxes and management practices. In order to support farm management decisions, it is essential to describe the farm internal structures and the relationships between soil–plant–animal–environment (Küstermann et al., 2008). Thus, it becomes possible to disclose the causes of different N utilisation, to identify weak spots and to elaborate strategies for optimising N cycles on-farm scale (Oenema et al., 2003; Watson et al., 2002).

Yet, the numerous attempts of N balancing have so far not yielded a standardised method, since the objectives are very diverse. As a consequence, results are only comparable if the balancing methods have been clearly defined. According to Halberg et al. (2005) and Goodlass et al. (2003), N balancing models can be classified according to:

- System level and spatial breakdown: farm scale (farm gate balance), crop production (field balance or soil surface balance), livestock keeping (barn balance).
- N fluxes and N pools considered.
- Balancing coefficients and algorithms.
- The database: measured values, estimates, assumptions or statistical data.

The paper deals with the introduction and application of a N balancing model designed for N management at the farm level. It describes agricultural farms as systems which respond to interferences like structural changes, alterations in intensity and technology. All subsystems of a farm (soil–plant–animal–environment) are linked via N fluxes which allow, for example, the simulation of interactions between crop production and animal husbandry.

To verify the efficiency and validity of the model, it has been used in the experimental farm Scheyern in southern Germany. Here, a long-term experiment was started in 1992 comprising an organic (org) and a conventional (con) farming system, with the aim of analysing their impacts on ecosystems (Schröder et al., 2002, 2008). During the experimental period different use intensities (phases of intensification and extensification) were applied. All management information has been recorded in detail; the resulting effects on N cycles were analysed by measurements and modelling of all relevant N fluxes and N pools.

The model allows one to estimate soil surface balance, barn balance and farm gate balance and to link these partial balances to an aggregated system balance, in order to evaluate management effects on the N surplus, N utilisation and N emissions and to show optimisation potentials. Measurement records help to estimate the degree of accuracy achieved with the model in describing N cycles and in disclosing the extent of errors in N balance sheets. General conclusions are drawn on the recommended procedure of N balancing, in order to make optimal use of them in farm management.

2. Methods and materials

2.1. Modelling approach

The applied approach of N balancing is an integrated part of the model REPRO (REPROduction of soil fertility (Hülsbergen, 2003)). REPRO is a software for evaluating and optimising the environmental effects of farming systems. The model contains interlinked submodels which support the balancing of energy (Hülsbergen et al., 2001; Deike et al., 2008), carbon fluxes and greenhouse gas emissions (Küstermann et al., 2008), estimates of the potential of harmful soil compaction (Rücknagel et al., 2007) and erosion risk (Siebrecht and Hülsbergen, 2008a) as well as the determination of biodiversity (Siebrecht and Hülsbergen, 2008b).

REPRO has integrated methods for calculating N fluxes and N pools on the basis of available farm data, for example symbiotic N_2 fixation, N fluxes in livestock keeping and the N turnover in the soil. These methods will be described below.

- *Symbiotic N_2 fixation*. The N_2 fixation of legumes is calculated with a distinction made between the N quantities in harvested products and those in residues. It is assumed that (1) N_2 fixation rises with increasing yield (Carlsson and Huss-Danell, 2003; Hogh-Jensen et al., 2004) and (2) that a crop specific share in the N uptake is contributed by N_2 fixation (N_{dfa} = nitrogen derived from the atmosphere). The N_{dfa} values are differentiated according to cropping conditions and content of plant available N in the soil. The N quantities in roots, crop residues and rhizodeposition are estimated by use of the crop specific parameters dry matter (DM) ratio (r_{DM} = DM residues · DM $yield^{-1}$) and N Content ratio (r_N = N content residues · N content $yield^{-1}$) (Hülsbergen, 2003).The symbiotically fixed N quantity in the yield (NY_{Sym} [kg ha^{-1} yr^{-1}]) is estimated with account of fresh matter yield (Y [kg ha^{-1} yr^{-1}]), dry matter content (DM [%]), N content in the dry matter (N [kg N kg^{-1}]), share of legumes (L [%]) and N_{dfa} (Eq. (1)).

$$NY_{Sym} = Y \cdot DM \cdot 0.01 \cdot N \cdot L \cdot 0.01 \cdot N_{dfa} \quad (1)$$

  The symbiotically fixed N quantity in the residues (NR_{Sym} [kg ha^{-1} yr^{-1}]) is estimated with account of dry matter ratio (r_{DM}) and N content ratio (r_N) (Eq. (2)):

$$NR_{Sym} = NY_{Sym} \cdot r_{DM} \cdot r_N \quad (2)$$

- *N turnover in livestock management*. The N fluxes in livestock management are handled separately according to livestock species, pasturing and housing. N excretion (N_{Ex} [kg ha^{-1} yr^{-1}]) is quantified by analysing the N input with feed (N_F [kg ha^{-1} yr^{-1}]), the changing N quantity in the live weight of animals (ΔN_{LW} [kg ha^{-1} yr^{-1}]) and the nitrogen in animal products (N_{AP} [kg ha^{-1} yr^{-1}]) (Eq. (3)) with regard to the digestibility (D) of the crude protein (D_{CP} [%]) (Eq. (4)). As

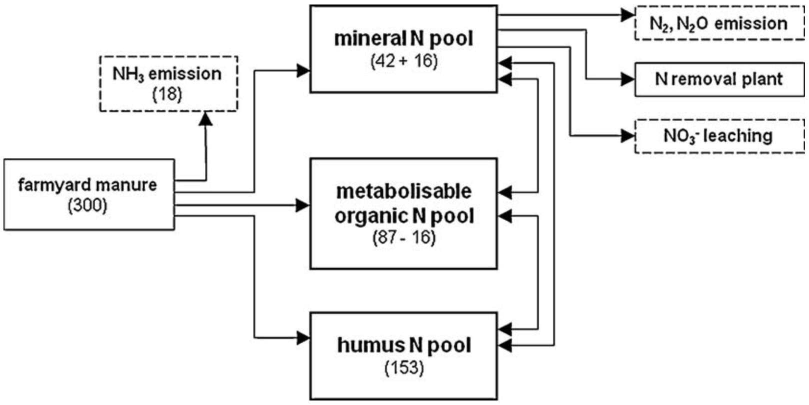

Fig. 1. N pools and N fluxes in the module Soil N Turnover: in brackets the delivered amount of nitrogen after application of 300 kg N ha^{-1} as farmyard manure (FYM).

precondition for N balancing according to Eq. (3), it was assumed: N supplied with feedstuffs enhances either the live weight or leaves the animal body byproducts (milk, wool, eggs) or faeces (N_{Faec} [kg ha^{-1} yr^{-1}], Eq. (4)) and urine (N_U [kg ha^{-1} yr^{-1}], Eq. (5)).

$$N_{Ex} = N_F - \Delta N_{LW} - N_{AP} \quad (3)$$

$$N_{Faec} = N_F \cdot (100 - D_{CP}) \cdot 0.01 \quad (4)$$

$$N_U = N_{Ex} - N_{Faec} \quad (5)$$

The approach furnishes an estimate of the influence of different feeding regimes and performance levels on the excreta output by quantity and quality. Based on housing system (solid/liquid manure) and manure handling technology (manure storage and processing), estimates of the manure output and its chemical composition as well as the N loss potential are obtained.

- *N turnover in the soil*. In the module Soil N Turnover (Abraham, 2001), N mineralisation and immobilisation are computed. The module includes three interrelated N pools (Fig. 1), the mineral N pool (plant available N), the metabolisable organic N pool and the humus N pool (inert organic N), the last two pools summed up to soil organic nitrogen (SON). Manure applications replenish the different N pools depending on applied N rate, organic and mineral N content and humus accumulation rate. In the example (Fig. 1) 300 kg N ha^{-1} yr^{-1} (farmyard manure, FYM) were applied, 60 kg N ha^{-1} yr^{-1} (20%) of it in mineral form (NH_4). Taking account of the conditions of application (soil type, time until incorporation) NH_3 emissions are computed; in our example the NH_3 loss reached 30% of the supplied NH_4-N. The N quantity immobilised in the humus N pool is determined by means of C balancing (Hülsbergen, 2003; Küstermann et al., 2008). Depending on the chemical components and the degree of decomposition, a specific C humification rate is allocated to each organic fertiliser (Hülsbergen, 2003). N and C accumulation in humus are coupled. Assuming a C:N ratio of 17:1, a FYM dose of 300 kg N ha^{-1} would supply to the soil about 5100 kg C ha^{-1}. On the basis of a mean C accumulation rate of 0.30, 1530 kg C ha^{-1} are stored as soil organic carbon. Supposing a C:N ratio in the soil of 10:1, this would correspond to an N immobilisation of 153 kg N ha^{-1} (Fig. 1). Thus, the organic N pool gains by 87 kg N ha^{-1}. N delivery by mineralisation (in the example 16 kg N ha^{-1}) was estimated with regard to the day of application and the Biological Active Time (Franko et al., 1995), a site related parameter characterising the conditions of N turnover.
- *Denitrification losses* from soils ($N_{DL(act)}$ [kg N ha^{-1} yr^{-1}]) are calculated according to Hermsmeyer and van der Ploeg (1996) (Eq. (6)). For each site, the maximum denitrification level ($N_{DL(max)}$ [kg N ha^{-1} yr^{-1}]) is determined by taking account of the soil organic matter content, soil texture, dry bulk density, field capacity and pore volume as well as the pH value. The real denitrification is calculated according to Köhne and Wendland (1992). The considered factors are the maximum denitrification, a site specific constant k derived from the turnover conditions (k [mg NO_3-N kg^{-1} soil]) and the N concentration ($c(N)$ [mg NO_3-N kg^{-1} soil]) derived from the mineral N pool (see Fig. 1).

$$N_{DL(act)} = N_{DL(max)} \cdot c(N) \cdot (k + c(N))^{-1} \quad (6)$$

- For calculating the *N losses by leaching* N_L [kg NO_3-N ha^{-1} yr^{-1}], the following N inputs [kg N ha^{-1} yr^{-1}] are considered, (Eq. (7)):

$$N_L = N_{Dep} + N_{SYM} + N_{MF} + N_{Min\_OF} + N_{Min\_Pool} + N_{Min\_SON} - N_Y - \Delta SON - N_{NH_3L} - N_{DL(act)} \quad (7)$$

where N_{Dep} is the N deposition, N_{SYM} is the symbiotic N_2 fixation, N_{MF} the mineral N fertilisation, N_{Min_OF} are the soluble N quantities from organic fertilisers, N_{Min_Pool} are the N quantities in the mineral N pool from the preceding year as well as N_{Min_SON} which is the N mineralisation from the SON pool. A leaching risk exists for those N quantities which are not organically fixed, neither in harvested products (N_Y) nor in the soil (ΔSON) or which left the soil as ammonia (N_{NH_3L}) and via denitrification ($N_{DL(act)}$). For calculating the nitrate concentration in the leachate (N_{CONZLe} [mg NO_3 l^{-1}]), leachate rate (LR [mm yr^{-1}]) and leachate factor (LF, Eq. (10)) have to be determined, the latter derived from the soil properties (pore volume, available field capacity (aFC [mm])) (Eq. (11)). The leachate rate is calculated (Eq. (8)) with regard to the precipitation [mm] during ($Prec_{GP}$) and beyond ($Prec_{bGP}$) the growth period, the plant available soil water (W_{PaW} [mm]) and the potential evapotranspiration (ETP [mm a^{-e1}]) (Renger and Strebel, 1980), the latter being estimated in dependence on the global radiation (RG [J cm^{-2}]) and the temperature of the atmosphere (T [°C]) (Eq. (9)) (Wendling, 1993).

$$LR = 0.92 \cdot (Prec_{bGP}) + 0.61 \cdot (Prec_{GP}) - 153 \cdot (\log W_{PaW}) - 0.12 \cdot (ETP) + 109 \quad (8)$$

$$ETP = (RG + 90) \cdot (T + 22) \cdot (150 \cdot (T + 123))^{-1} \quad (9)$$

$$LF = LR \cdot aFC^{-1} \quad (10)$$

$$N_{CONZLe} = N_L \cdot LR^{-1} \cdot LF \cdot 443 \quad (11)$$

N surplus and N utilisation were computed for the cropping system (soil surface balance), for the livestock system (barn balance) and on-farm scale (farm gate balance). Combining the balances furnishes a system balance, which allows quantification all relevant N fluxes. N surplus [kg ha^{-1} yr^{-1}] means the potential N loss by the system; it has been defined as:

$$\text{N surplus} = \sum \text{N input} - \sum \text{N output}. \tag{12}$$

The apparent utilisation of the nitrogen supplied to the system was defined as:

$$\text{N utilisation} = \sum \text{N output} \cdot \left(\sum \text{N input}\right)^{-1} \tag{13}$$

2.2. Experimental farm

The model approach has been applied in the experimental farm Scheyern, located 40 km north of Munich 48°N30.0′, 11°E20.7′. The research station is situated 445–498 m above sea level in a hilly landscape derived from tertiary sands and clays which are partly covered by loess. Soil types and soil properties vary broadly; however, most of the soils have a loamy texture and are classified as Cambisols and Eutrochrepts. The mean annual precipitation is 833 mm; the mean annual temperature 7.4 °C (Auerswald et al., 2000). The reference period includes years whose weather conditions deviated clearly from the long-term mean values (Table 1); for example the extremely dry and warm year 2003, when strong heat and drought stress occurred with only low leachate rates. Daily weather records were used for the modelling of Soil N Turnover and nitrate leaching.

In 1992 two different farming systems were established under similar site conditions:

- A mixed organic farm (org) with 31.3 ha arable land, 18.2 ha permanent grassland, and a suckler cow herd,
- and a conventional arable farm (con) with 30.4 ha arable land.

The aim was to analyse the effects of different management systems on the agroecosystem and to find ways to make land use more sustainable (Schröder et al., 2002, 2008).

The stock density of the organic farm was gradually enhanced from 0 LSU ha^{-1} (in 1992) to 1.4 LSU ha^{-1} (from 1999 to 2002) and then again continuously reduced. Thus, different intensities and mass fluxes on-farm scale were established.

The conventional farm has specialised on cash crop production. From 1993 to 2002, silage maize was sold for an equivalent quantity of slurry.

The organic system has the following crop rotation:

(1) Grass–clover–alfalfa (GCA) (*Lolium perenne* L. + *Trifolium pratense* L. + *Medicago sativa* L.), (2) potatoes (*Solanum tuberosum* L.) + mustard, undersown (*Sinapis alba* L.), (3) winter wheat (*Triticum aestivum* L.), (4) sunflower (*Helianthus annuus* L.) + GCA, undersown, (5) GCA, (6) winter wheat, and (7) winter rye (*Secale cereale* L.) + GCA, undersown.

The conventional system has the crop rotation: (1) potatoes + mustard as catch crop, (2) winter wheat, (3) maize (*Zea mays* L.) + mustard as catch crop, and (4) winter wheat.

In both systems, each crop of the crop rotation is grown in each year, with the crops rotating in the fields. Since the fields of the crop rotation are not of exactly the same size and soil quality (in the organic system: 4.5 ha on average, variation coefficient: 0.15, in the conventional system: 7.6 ha on average, variation coefficient: 0.11) the N balance was affected, but negligibly. Tillage is adapted to the cropping systems. In the seven-field organic rotation, usually three operations with a mouldboard plough are carried out and two with a chisel plough. In the years of grass–clover–alfalfa cultivation, tillage is omitted completely. The conventional crop rotation does completely without ploughing. Prior to the row crops, mustard is planted as a cover crop and maize is directly planted into frozen mustard without any tillage.

Tillage and crop rotation are coordinated in order to guarantee ground coverage as protection against erosion as long as possible and an optimal use of the vegetation period by main and catch crops, thus supporting high N utilisation.

The two experimental systems (org) and (con) are typical for the region in respect of their structure, intensity and production technology. The differences in crop rotation (org: legume-based and diverse, con: no legumes and specialised), input (org: no pesticide use and no mineral N, con: intensive pesticide use, high mineral N input) and tillage (org: tillage with mouldboard plough, con: conservation tillage) characterise exactly the situation in the Bavarian tertiary hills and allow a practice-related system analysis to be made.

For more than 15 years, the cropped farm area has been subjected to an intensive sampling programme (Auerswald et al., 2000). Yields, dry matter and nutrient contents in the harvested products have been surveyed for each field and subfield separately. The FYM doses have been determined by weighing, the nutrient contents analytically. In a 50 m × 50 m sampling grid, soil organic carbon (SOC), soil organic nitrogen (SON) and nutrient contents have been monitored at 5-year intervals. In the topsoil of the organic farm (90 sampling points), SOC levels [%] reached 1.40 on average (0.78–2.69); SON [%] 0.135 (0.085–0.272). In the integrated farm (104 sampling points), SOC averaged 1.26 (1.05–2.08) and SON 0.122 (0.101–0.207) (sampled in 2005). At some sampling points and on partial areas, N fluxes have been measured over many years, for example N_2O emissions (Flessa et al., 2002) and nitrate losses (Hellmeier, 2001; Honisch et al., 2002), but also the N_2 fixation of grass–clover–alfalfa with high spatial resolution (Heuwinkel et al., 2005).

The N balance of the experimental farm Scheyern and the factors influencing N fluxes and N pools were analysed for two reference periods:

- Averaging the years 1999–2002, in order to compare the two systems (org vs. con) at the moment of highest intensity (highest livestock density, highest N input).

Table 1
Meteorological data of the experimental station Scheyern during the period of investigation.

	Unit	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Annual precipitation	l m^{-2}	961	852	786	728	658	869	899	911	966	1015	495	736	901	759
Precipitation (April to September)	l m^{-2}	625	543	468	491	384	463	509	577	502	516	244	401	615	474
Mean annual temperature	°C	7.8	10.8	8.5	6.3	7.5	8.6	8.6	8.7	8.4	9.0	8.5	8.1	7.7	8.5
Mean temperature (April to September)	°C	13.7	16.1	13.4	12.5	12.8	14.1	14.7	13.8	13.7	14.1	15.8	13.8	14.3	14.8
Annual global radiation	kWh m^{-2}	988	1102	1094	1096	1128	1247	1111	1116	971	1198	1305	1101	1086	1112

Table 2
Nitrogen soil surface balance of the organic crop rotation, averaging the years 1999–2002.

Field	Crop	N input			Yield	Straw/green manure[a]	N output	N surplus[b]	N utilisation[c]
	+ catch crop[d]	N_2 fixation (kg N ha^{-1})	FYM (kg N ha^{-1})	Slurry (kg N ha^{-1})	MP (BP)[e] (Mg DM ha^{-1})	(kg N ha^{-1})	MP (kg N ha^{-1})	(kg N ha^{-1})	kg N (kg N)$^{-1}$
1	Grass–clover–alfalfa (GCA)	261			11.8		304	–27	1.10
2	Potatoes		186		4.9	31	66	136	0.33
	+ undersown mustard					*46*			
3	Winter wheat		99	18	2.4 (2.2)		59	74	0.44
4	Sunflower		82	8	1.6	39	46	60	0.34
	+ undersown GCA	*31*				*46*		*31*	
5	GCA	236			10.9		283	-31	1.12
6	Winter wheat		26	23	3.1 (2.8)		82	-17	1.26
7	Winter rye		95	17	2.9 (2.9)		64	64	0.79
	+ undersown GCA	*50*			*2.9*		*76*	*-26*	
	Crop rotation	**83**	**70**	**9**	**6.9**	**23**	**140**	**38**[f]	**0.77**[g]
	Grassland	33	10	95	6.2		136	18	0.88
	Agricultural area (AA)	**60**	**43**	**48**	**6.6**	**13**	**138**	**29**[h]	**0.82**[i]

[a] The straw of sunflowers, potato vines, non-harvested biomass of GCA and the cover crop mustard remained in the field and were not considered as N output or N input.
[b] N surplus = ΣN input – ΣN output, N input = N_2 fixation + FYM + slurry + N deposition (av. 16 kg N ha^{-1} yr^{-1}).
[c] N utilisation = (ΣN output) · (ΣN input)$^{-1}$.
[d] All information on catch crops typed in italics.
[e] MP = harvested main products (GCA biomass, grain, sunflower, potato), BP = harvested by-products (straw of winter wheat and winter rye).
[f] With consideration of changes in soil organic nitrogen (ΔSON = 35 kg N ha^{-1} yr^{-1}) the N surplus decreased to 3 kg N ha^{-1} yr^{-1}, mean of crop rotation.
[g] With consideration of ΔSON (=35 kg N ha^{-1} yr^{-1}) the N utilisation increased to 0.98, mean of crop rotation.
[h] With consideration of ΔSON (=20 kg N ha^{-1} yr^{-1}) the N surplus decreased to 9 kg N ha^{-1} yr^{-1}, mean of agricultural area (AA).
[i] With consideration of ΔSON (=20 kg N ha^{-1} yr^{-1}) the N utilisation increased to 0.94, mean of agricultural area (AA).

- Development from 1993 to 2006, in order to investigate the influence of structural changes on N surplus and N utilisation.

The results in the balance sheets are compared with measured values, in order to estimate the scope of error inherent in the model and to verify the plausibility of the model statements.

3. Results

3.1. Nitrogen soil surface balance from 1999 to 2002

The results of measurements and N input balancing, system performance (yield, N outputs), N losses and N utilisation are presented separately for the organic and the conventional system. The chosen experimental design allows a system comparison (org vs. con) of the same crops (wheat, potatoes) and of the crop rotation (soil surface balance).

The 7-year organic crop rotation is based on legumes (Table 2). It comprised of two fields (28.6%) with grass–clover–alfalfa, which reached a symbiotic nitrogen fixation of av. 248 kg N ha^{-1} yr^{-1} and a high yield (11.4 Mg DM ha^{-1} yr^{-1}). The share of legumes is 60% of the biomass. According to the stock density of 1.4 LSU ha^{-1}, each hectare of arable land received 70 kg N as FYM and 9 kg N as slurry. The crops differed clearly in their N outputs (N quantity in the harvested biomass): potatoes, cereals and sunflowers reached only about 15–30% of the N output with grass–clover–alfalfa. The high mean yield (6.9 Mg DM ha^{-1} yr^{-1}) and N output (140 kg N ha^{-1} yr^{-1}) in the organic crop rotation resulted mainly from the grass–clover–alfalfa mix.

Table 3
Nitrogen soil surface balance of the conventional crop rotation, averaging the years 1999–2002.

Field	Crop	N input		Yield	Straw/green manure[a]	N output	N surplus[b]	N utilisation[c]
	+ catch crop[d]	Mineral N (kg N ha^{-1})	Slurry (kg N ha^{-1})	MP[e] (Mg DM ha^{-1})	(kg N ha^{-1})	MP (kg N ha^{-1})	(kg N ha^{-1})	kg N (kg N)$^{-1}$
1	Potatoes	90		8.9	75	128	–22	1.02
	+ mustard	*20*			*127*		*20*	
2	Winter wheat	160	46	5.9	28	144	78	0.65
3	Maize	130	58	13.8		178	26	0.79
	+ mustard	*20*			*127*		*20*	
4	Winter wheat	160	28	5.5	30	149	55	0.73
	Crop rotation	**145**	**33**	**8.5**	**97**	**150**	**44**[f]	**0.79**[g]

[a] See Table 1.
[b] N surplus = ΣN input – ΣN output. N input = mineral N + slurry + N deposition (av. 16 kg N ha^{-1} yr^{-1}).
[c] N utilisation = (ΣN output) · (ΣN input)$^{-1}$.
[d] All information on catch crops typed in italics.
[e] MP = harvested main products (grain, potato, maize silage).
[f] With consideration of ΔSON (−24 kg N ha^{-1} yr^{-1}) the N surplus increased to 68 kg N ha^{-1} yr^{-1}, mean of crop rotation.
[g] With consideration of ΔSON (−24 kg N ha^{-1} yr^{-1}) the N utilisation decreased to 0.69, mean of crop rotation.

The N balance revealed rather different N surplus and N utilisation levels for the examined crops. The highest N surplus (136 kg ha^{-1} yr^{-1}) and the lowest N utilisation (0.33) were computed for potatoes; negative N surpluses and N utilisation values > 1.0 were measured on crop rotation fields 1 and 5 (grass–clover–alfalfa) and 6 (winter wheat) (Table 2). Within the crop rotation, N transfer takes place: potatoes, for example, received 186 kg N ha^{-1} yr^{-1} with FYM, but only about 40% (75 kg N ha^{-1} yr^{-1}) was plant available during the growth period; the remaining amount was stored as soil organic nitrogen (SON). The module Soil N Turnover showed an increase of SON (35 kg ha^{-1} yr^{-1}) averaging the entire crop rotation, which can be attributed above all to legume growing and FYM supply. Considering ΔSON, the N surplus in the crop rotation decreased to 3 kg ha^{-1} yr^{-1}, while N utilisation increased to 0.98 (Table 2).

Table 2 shows also the N balance of the grassland in addition to that of the crop rotation. The grassland was used both as pasture and meadow. Nitrogen was supplied via the excreta of grazing cattle as well as with slurry and FYM. The N output (136 kg ha^{-1} yr^{-1}) corresponds to the N amount in the forage. Since grazing was supplemented by stall feeding, part of the forage N from the grassland reached the arable area as slurry and FYM after metabolisation by livestock. This demonstrates the connection of arable land and grassland via the N fluxes in livestock keeping. As we deal with permanent grassland, a steady state in the soil (ΔSON, 0 kg N ha^{-1} yr^{-1}) is assumed. The N surplus amounted to 18 kg ha^{-1} yr^{-1} and thus ranked above the level of the crop rotation.

The situation in the conventional crop rotation was completely different (Table 3). No legumes were included and thus the main N input came from mineral N (145 kg ha^{-1} yr^{-1}). The yield (8.5 Mg DM ha^{-1} yr^{-1}) exceeded that of the organic crop rotation by 23%; the N removal (150 kg ha^{-1} yr^{-1}) was about 7% higher than in the organic rotation. Potatoes and winter wheat, which were grown in both crop rotations, showed much broader yield deviations (con vs. org): DM yield of potatoes, +82%; N removal by potatoes, +94%; DM yield of winter wheat (grain), +107%; N removal by winter wheat (grain + straw), +108%. Averaging the crop rotation, fertiliser N in the conventional system was well utilised as shown by high yields. N utilisation amounted to 0.79 and N surplus to 44 kg ha^{-1} yr^{-1}. However, for the conventional crop rotation a decline of the humus stock was computed (ΔSOC, −0.25 Mg ha^{-1} yr^{-1}), which was confirmed by field sampling (Küstermann et al., 2008); this corresponds to ΔSON of −24 kg ha^{-1} yr^{-1} (Table 3). Taking this into account increases the N surplus to 68 kg ha^{-1} yr^{-1}, which implies a decline of N utilisation to 0.69.

3.2. N cycles from 1999 to 2002

We regard N fluxes and N pools in both management systems on the scale of the agricultural area (arable land + grassland) in order to analyse the relations between the subsystems. Due to the structural differences between the farming systems, N fluxes are totally different. The organic system is based on nitrogen cycling, the conventional one on nitrogen just passing through the farm (Figs. 2 and 3).

In the organic system, N_2 fixation was the most important N input (60 kg ha^{-1} yr^{-1}). Considerable forage quantities (34 kg N ha^{-1} yr^{-1}) were imported from adjacent areas under organic management and enhanced the N fluxes (Fig. 2). The major part of the biomass remained as forage within the farm internal mass cycle; only about 22% of the harvested biomass (28 kg N ha^{-1} yr^{-1}) were exported as cash crop.

Cash products from livestock husbandry (sold cattle) exported 22 kg N ha^{-1} yr^{-1}. This implies, in relation to the N input of 138 kg ha^{-1} yr^{-1}, an N utilisation value of 0.16, but if the farmyard manure and slurry (95 kg N ha^{-1} yr^{-1}) are regarded as by-product, N utilisation is 0.85. The exported farmyard manure N is negligible (4 kg ha^{-1} yr^{-1}).

The soils received 104 kg N ha^{-1} yr^{-1} via FYM as well as straw and green manure. Summarising all N inputs including the mean N deposition measured in Scheyern (16 kg ha^{-1} yr^{-1}, Hellmeier, 2001) and ΔSON (20 kg ha^{-1} yr^{-1}) as well as the N output (N removal by the plants), we arrive at a N surplus of 9 kg ha^{-1} yr^{-1} on agricultural area scale. Summarising all N losses (N_2O, N_2, NH_3,

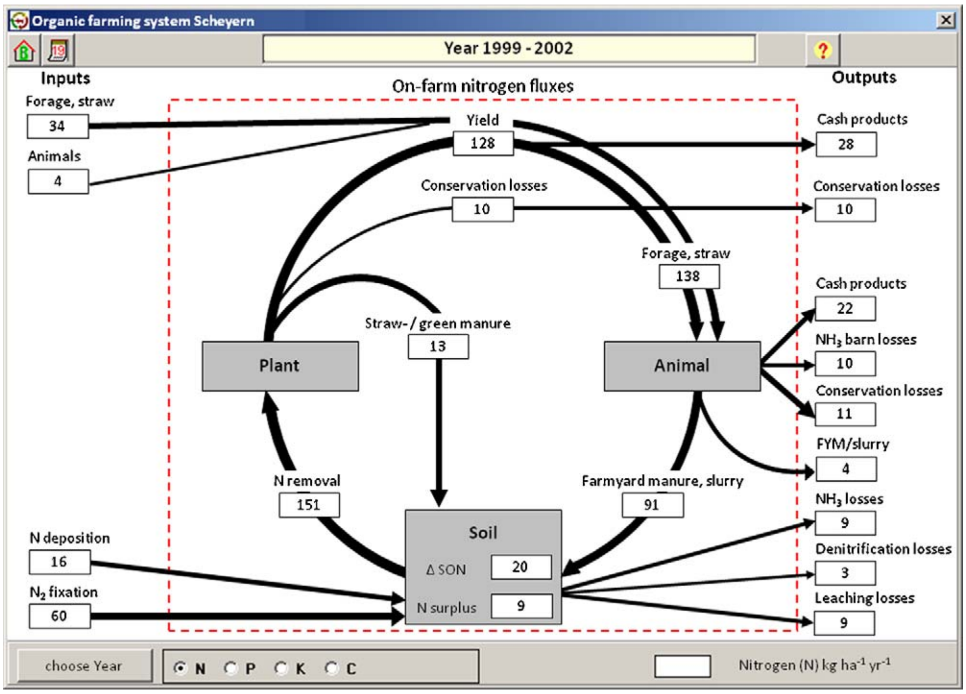

Fig. 2. On-farm nitrogen cycle of the organic farming system Scheyern, kg N ha^{-1} yr^{-1} (av. 1999–2002), sreenshot of the model REPRO.

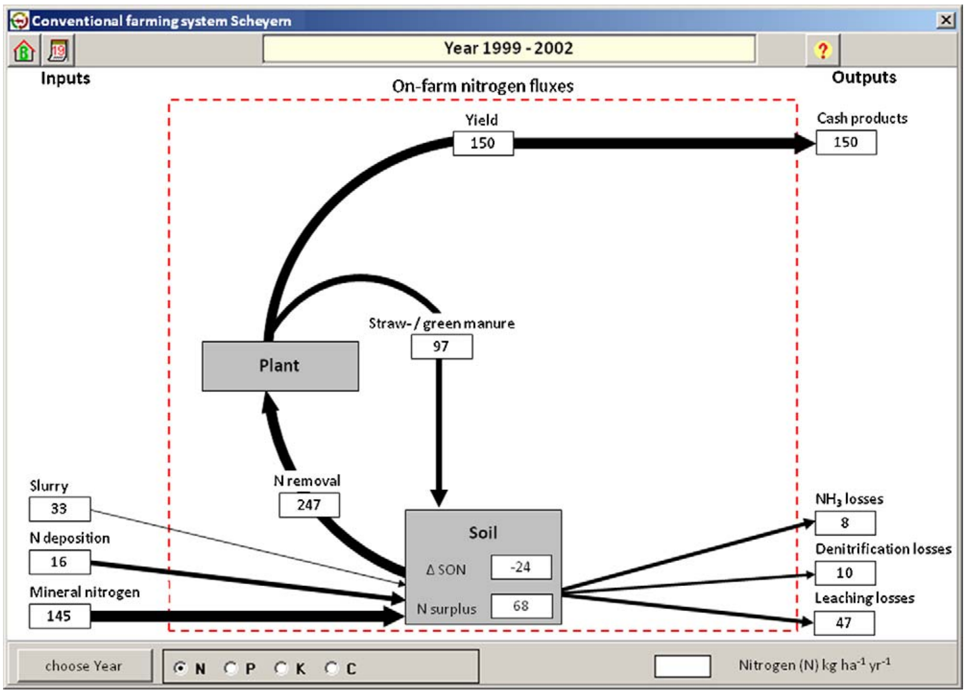

Fig. 3. On-farm nitrogen cycle of the conventional farming system Scheyern, kg N ha^{-1} yr^{-1} (av. 1999–2002), sreenshot of the model REPRO.

NO_3) they exceeded the annual N surplus, because calculations of the Soil N Turnover included all soil N pools and also the N transfer from previous years.

The conventional farming system is based on the application of mineral nitrogen. From a neighbouring farm, 33 kg N ha^{-1} yr^{-1} were imported as slurry. The N removal averaged 247 kg ha^{-1} yr^{-1}. Bound in cash crops, very high N quantities were exported (150 kg ha^{-1} yr^{-1}); this N amount exceeded even the input of mineral N.

As the entire straw quantity remained in the farming system and catch crops were grown on 50% of the area, N supply by slurry, straw, green manure, was higher (130 kg ha^{-1} yr^{-1}) than in the organic farm despite missing livestock. Nevertheless, we recorded a decline in the humus stock (ΔSON, −24 kg ha^{-1} yr^{-1}) due to the intensive crop rotation (50% potatoes and maize) and the lesser stability of straw and green manure against decomposition compared with FYM. N surplus (68 kg ha^{-1} yr^{-1}) and N losses by leaching (47 kg ha^{-1} yr^{-1}) were markedly higher than in the organic farm.

3.3. N balance from 1993 to 2006

Farm gate balance. The development of the organic system in Scheyern included the establishment of suckler cows and a gradual increase of the stock density from 0.52 (1993/1994) to 1.40 LSU ha^{-1} (2001/2002). Afterwards, stock numbers were reduced again in order to simulate a shift to cash crop production (Table 4). A distinction must be made between a phase of intensification until 2001/2002 and a phase of extensification after 2003/2004. The structural changes had a clear influence on the N balances at a farm gate scale (Table 4). The increasing stock density entailed the purchase of extra feed, because the cattle could not be fully provided with forage from own production. An increase of N_2 fixation was recorded by 2001/2002, because the use intensity had risen together with the yields of grass–clover–alfalfa. In the phase of extensification, N_2 fixation declined because the biomass of grass–clover–alfalfa was left on the ground as mulch (negative feedback to N_2 fixation, Heuwinkel et al., 2005).

Table 4
Development of stock density and N balance in the organic farm Scheyern; farm gate scale [kg N ha^{-1} yr^{-1}].

Year	1993/1994	1995/1996	1997/1998	1999/2000	2001/2002	2003/2004	2005/2006
Livestock density [LSU ha^{-1}]	0.52	0.62	0.86	1.38	1.40	0.91	0.10
Input[a]	72	63	88	107	121	88	52
Feed	0	1	22	28	41	21	0
N_2 Fixation	50	43	49	59	61	47	35
Output[b]	33	30	39	50	59	43	36
Plant products	29	23	27	24	32	30	34
Animal products	4	7	12	22	23	13	2
N surplus[c]	39	33	49	57	62	45	16
N utilisation [kg N (kg N)$^{-1}$][d]	0.46	0.48	0.44	0.46	0.49	0.49	0.69

[a] Input = N_2 fixation + feed + animals + N deposition (av. 16 kg N ha^{-1} yr^{-1}).
[b] Output = plant products + animal products + exported organic manure.
[c] N surplus = ΣN input − ΣN output.
[d] N utilisation = (ΣN output) · (ΣN input)$^{-1}$.

Table 5
Development of N balance and N losses in the organic farm Scheyern; crop rotation scale [kg N ha^{-1} yr^{-1}].

Results of N balance							
Year	1993/1994	1995/1996	1997/1998	1999/2000	2001/2002	2003/2004	2005/2006
Input[a]	130	124	147	173	183	146	97
N_2 fixation	68	54	63	80	84	64	48
FYM + slurry	46	54	68	77	83	66	33
Output[b]	110	85	108	137	143	112	55
N surplus[c]	20	39	39	36	40	34	42
ΔSON	14	13	21	33	38	6	17
N surplus with ΔSON[d]	6	26	18	3	2	28	25
N utilisation [kg N (kg N)$^{-1}$][e]	0.95	0.77	0.86	0.98	0.98	0.80	0.67
Results of the module Soil N Turnover							
NH_3 volatilisation	4	4	6	7	6	8	1
N_2, N_2O denitrification	7	8	5	6	8	7	9
NO_3 leaching	12	12	10	16	24	17	15
NO_3 concentration [mg (1000 g)$^{-1}$]	14	19	18	19	23	43	22

[a] Input = N_2 fixation + FYM + slurry + N deposition (av. 16 kg N ha^{-1} yr^{-1}).
[b] Output = harvested main products + harvested by-products.
[c] N surplus = ΣN input – ΣN output.
[d] N surplus – ΔSON.
[e] N utilisation = (ΣN output) · (ΣN input – ΔSON)$^{-1}$.

The highest N output in products (55 kg ha^{-1} yr^{-1}) was recorded at the peak of management intensity; afterwards it decreased by nearly 40%. N utilisation remained on nearly the same level throughout the reference period (0.44–0.49); eventually, in 2005/2006 it increased to 0.69, because the number of cattle and the involved N losses declined. The N surplus values in the farm gate balance are related to the stock density (Table 4); with decreasing stock numbers N surplus fell from 62 to 16 kg ha^{-1} yr^{-1}.

The farm gate balance provides no information about the N loss in the subsystems, for example the N surplus in crop production. Therefore, we additionally analysed the development of the soil surface balance in the organic (Table 5) and in the conventional crop rotation (Table 6).

Soil surface balance. In the soil surface balance, N inputs and N outputs rose with increasing stock density (Table 5). After the shift to organic management, yields and N removals remained constant for 5 years; with the intensification of the N cycle N removal increased to a maximum of 143 kg ha^{-1} yr^{-1} and declined to 55 kg ha^{-1} yr^{-1} in the subsequent period of extensification.

With the exception of the years 1993/1994, the N surplus of the soil surface balance remained on approximately the same level (34–42 kg N ha^{-1} yr^{-1}), despite rising stock density. If ΔSON is considered in N balancing, we observed the lowest N surplus and the highest N utilisation in the phase of maximum stock density (1999–2002). The available N quantities (legume N and FYM N) were transformed to yield or increased the SON stock.

While for each year separate N balances were computed, the module Soil N Turnover couples combines the single years for the determination of N losses (see Section 2). The program estimated a gradual rise of the N quantity in the pool "metabolisable organic N" and thus a continuous increase of the N mineralisation potential. That is the reason why the computed NO_3 loss and NO_3 concentration in leachate increased and even exceeded the N surplus in some years.

In the conventional system, soil surface balance and farm gate balance are identical due to the lack of livestock. Other than in the organic system, the highest use intensity (related to the N input) was recorded as early as in 1997/1998; later the N input was

Table 6
Development of N balance and N losses in the conventional farm Scheyern; crop rotation scale [kg N ha^{-1} yr^{-1}].

Results of N balance							
Year	1993/1994	1995/1996	1997/1998	1999/2000	2001/2002	2003/2004	2005/2006
Input[a]	170	187	225	208	180	176	173
Mineral N	124	138	150	160	130	160	157
Slurry	30	33	59	32	34	0	0
Output[b]	118	120	130	146	155	160	156
N surplus[c]	52	67	95	62	25	16	17
ΔSON	–15	0	0	–19	–30	–27	–30
N surplus with ΔSON[d]	67	67	95	81	55	43	47
N utilisation [kg N (kg N)$^{-1}$][e]	0.64	0.63	0.57	0.64	0.74	0.79	0.77
Results of the module Soil N turnover							
NH_3 volatilisation	8	10	11	8	8	4	4
N_2, N_2O denitrification	10	11	10	12	9	17	12
NO_3 leaching	36	27	54	54	39	55	58
NO_3-N concentration [mg (1000 g)$^{-1}$]	45	48	88	62	36	142	86

[a] Input = mineral N + slurry + N deposition (av. 16 kg N ha^{-1} yr^{-1}).
[b] Output = harvested main products.
[c] N surplus = ΣN input – ΣN output.
[d] N surplus – ΔSON.
[e] N utilisation = (ΣN output) · (ΣN input – ΔSON)$^{-1}$.

continuously decreased in order to reduce the N surpluses (Table 6). As from 2003, no slurry was purchased.

The N output rose steadily because cash crop yields went up as a result of new varieties with higher productivity and improvements in the tillage system. Beginning in 2001, silage maize has been grown instead of grain maize, which brought also positive effects for the N output.

The highest N surplus (95 kg ha^{-1} yr^{-1}) and the lowest N utilisation (0.57) were recorded in the years 1997/1998; the highest N utilisation was obtained for the years 2003–2006. The stock of soil organic nitrogen decreased. With consideration of ΔSON, N surpluses increase and the total N loss potential was higher than in the organic system.

4. Discussion

4.1. Uncertainties of N balancing and comparison with measured values

An interpretation of N balance results requires knowledge of uncertainties on N surplus and N utilisation (Oenema et al., 2003; Öborn et al., 2003). Uncertainties in data input and parameters arise from a lack of data and knowledge, spatial and temporal variability on different scales and changes in items and parameters with time (Bengtsson, 2005).

In order to identify uncertainties and sources of error, results computed with the REPRO model were compared with results of N balancing according to the German Federal Fertilisation Act and Ordinance (GFAO; BMELF, 2006) and also with measured values from Scheyern (Table 7). N balancing according to GFAO is widely applied in Germany and therefore offers a good reference base. It is a simplification because only N inputs (fertilisation, N_2 fixation) and N outputs (N removal) are regarded. The N surplus is estimated without specifying N loss pathways and without consideration of ΔSON. The references in Table 7 include measured data from Scheyern and calculations made on that basis.

For the calculations of the N balance we assumed an N deposition of 16 kg N ha^{-1} yr^{-1}; based on long-term measurements in Scheyern (Hellmeier, 2001, Ruser et al., 2008). However, this value involves a potential underestimation of N deposition, because only wet N deposition had been determined (Russow and Böhme, 2005). Gauger et al. (2002) mention a slightly higher N deposition (22 kg N ha^{-1} yr^{-1}) for the region of Scheyern. Otherwise, N balancing according to GFAO neglects N deposition completely.

In organic farming systems N_2 fixation is the most important N input, and therefore the accuracy of its determination is decisive for the accuracy value of an N balance sheet. The share of legumes, biomass yield and N_2 fixation vary depending on weather and soil conditions and also on agronomic and cultural practices (Heuwinkel et al., 2002, 2005; Carlsson and Huss-Danell, 2003; Hogh-Jensen et al., 2004). For our model calculations we assumed a mean legume share of 60% in the biomass of GCA. Measurements in Scheyern confirm this value with a high degree of heterogeneity (Table 7, Heuwinkel et al., 2002). Considering yields and N contents measured in the biomass, a mean fixation of 242 kg N ha^{-1} yr^{-1} (GCA) and 98 kg N ha^{-1} yr^{-1} (crop rotation) was obtained (Heuwinkel et al., 2002; Ruser et al., 2008); this agrees well with results computed with the REPRO model. The N balance method according to GFAO furnishes lower N_2 fixation (Table 7); as influencing factors only yield and legume share were considered.

The SON and SOC contents measured at defined measuring points confirm the model results. The latest soil inventory of 2005, based on measured SON contents and dry bulk densities, revealed an increase of SON of 44 kg ha^{-1} yr^{-1} (org; $n = 90$) and a decrease of 38 kg ha^{-1} yr^{-1} (con; $n = 104$) since 1991 (Küstermann et al., 2008), whereas the computed results revealed a change in ΔSON of +35 kg ha^{-1} yr^{-1} (org) and ΔSON of –24 kg ha^{-1} yr^{-1} (con) for the

Table 7
Soil surface balance of the organic crop rotation. Comparison of the computed results (REPRO) with estimates according to German Federal Fertilization Act and Ordinance (GFAO; BMELF, 2006) and publications on measured and estimated N fluxes and N pools in the experimental station Scheyern.

Parameter	Unit	Soil surface balance			References and comments
		REPRO[a] 1999–2002	GFAO[b] 1999–2002	Reference[c]	
N input	kg N ha^{-1}	178	149		
N deposition	kg N ha^{-1}	16[d]	n.c.	30[d]	Gauger et al. (2002), regional mean value for the Bavarian tertiary hills
N_2 fixation (crop rotation)	kg N ha^{-1}	83	64	98	Ruser et al. (2008), mean of crop rotation 1995–2001
N_2 fixation, grass–clover–alfalfa (GCA)	kg N ha^{-1}	249	192	242[d]	Heuwinkel et al. (2002), mean value of one field
Dry matter yield, GCA	Mg ha^{-1}	11.3[d]	n.c.		
Share of legumes, GCA	%	60	n.c.	35[d]–73[d]	Heuwinkel et al. (2002), variability within a field
Ndfa (N derived from the atmosphere)	%	90	n.c.		
FYM and slurry	kg N ha^{-1}	79	85		
N output	kg N ha^{-1}	140	126		
Dry matter yield	Mg ha^{-1}	6.9[d]	6.9[d]		
N content in dry matter	%	2.02[d]	1.83		
N surplus	kg N ha^{-1}	38	9	51	Ruser et al. (2008), mean of crop rotation 1995–2001
N utilisation		0.77	n.c.		
ΔSON	kg N ha^{-1}	35	n.c.	18[d]–57[d]	Ruser et al. (2008), soil inventory 1991 and 2001, $n = 90$
NH_3 volatilisation	kg N ha^{-1}	6.5	n.c.	5.0	Ruser et al. (2008), mean of crop rotation 1995–2001
N_2O denitrification	kg N ha^{-1}	2.4	n.c.	4.0[d]	Ruser et al. (2008), mean of crop rotation 1995–2001
				1.0[d]–10.0[d]	Flessa et al. (2002),
NO_3 leaching	kg N ha^{-1}	20.0	n.c.	16.0[d]	Ruser et al. (2008), mean of crop rotation 1995–2001
N loss with surface run-off	kg N ha^{-1}	n.c.		1.4[d]–1.7[d]	Ruser et al. (2008)
NO_3-N concentration	mg (1000 g)$^{-1}$	21.0	n.c.		

n.c. not computed.

[a] Computed with REPRO with consideration of measured values (N deposition, yields, N contents), see Table 2.

[b] Estimated according to the German Federal Fertilization Act and Ordinance (GFAO; BMELF 2006).

[c] Publications on the experimental station Scheyern; measured or estimated N fluxes, N pools and N balances.

[d] Measured value

period 1999–2002, respectively. Most N balances are based on a simplified N steady state in the soil (ΔSON, 0 kg ha^{-1} yr^{-1}), for example N balances according to GFAO. Our calculations have shown that neglecting ΔSON would lead to an overestimation of N losses (org, Table 2) on the one hand and to an underestimation (con, Table 3) on the other. If ΔSON is included in the balance, the N surplus in the organic crop rotation decreases from 38 to 3 kg ha^{-1} yr^{-1} and increases from 44 to 68 kg ha^{-1} yr^{-1} in the conventional crop rotation. Accordingly, N utilisation would increase from 0.77 to 0.98 (org) and decrease from 0.79 to 0.69 (con), respectively, giving a completely different conclusion. A strong influence on the development of SON and SOC is exerted not only by the quantity but also by the quality of the supplied organic matter as well as by its components and the degree of decomposition (Drinkwater et al., 1998). However, accumulation and depletion in SON are temporarily limited and reach ΔSON = 0 with the establishment of new steady states (Johnson et al., 1995).

On the basis of the GFAO method the calculated N surplus is 4 kg N ha^{-1} yr^{-1}, that is 34 kg N ha^{-1} yr^{-1} lower than the N surplus computed by REPRO (Table 7). This leads to a 25% higher N utilisation. The reason is that the GFAO method ignores essential N fluxes (N deposition, ΔSON) or estimates them too low (N_2 fixation). Higher N output values result from differences in N content of the dry matter (Table 7). This has to be taken into account when N surplus results are to be evaluated. Since 2009 the GFAO admits a N surplus of not more than 60 kg N ha^{-1} yr^{-1}; in the REPRO method this corresponds to 90 kg N ha^{-1} yr^{-1}.

Our software model handles N balance data and also soil and climate parameters for calculating N pathways; this is an advantage compared with simple input/output accounting systems, for example the method proposed by the GFAO. By use of the module Soil N Turnover potential leaching losses of 10–24 kg N ha^{-1} yr^{-1} (Table 5) were computed. Measurements in soil hydrological stations and calculations on their basis for the organic crop rotation in Scheyern confirmed these N losses (Table 7, Ruser et al., 2008). The relationships between computed and measured N losses on different scales are the subject of numerous studies. The nitrate concentration in the leachate is very sensitive to annual fluctuations in precipitation (Langeveld et al., 2007). A close relation between N surplus and nitrate concentration in groundwater was found by Sieling and Kage (2006), Korsaeth and Eltun (2000) and Salo and Turtola (2006) in long-term soil surface balances. Numerous studies revealed a close relationship between N input and N_2O emissions (Flessa et al., 2002) and also between N surplus und N_2O emissions (Schils et al., 2008). Thus, the N surplus in the soil surface balance represents an integrative agri-environmental indicator that responds to various management (crop rotation, fertilisation) and influences several environmental sectors, mainly N emissions and soil fertility (SON).

4.2. Results of N balancing in the experimental farm Scheyern

Throughout a period of 14 years, the experimental farm Scheyern offered the unique chance of monitoring the development of N fluxes and pools in two management systems after structural and technological shifts. Both farming systems (org and con) passed several development stages which had a decisive influence on N balancing.

In the organic system, stock numbers were gradually increased, which involved an intensification of the N cycle. The highest intensity level was reached in 2001/2002 (=1.4 LSU ha^{-1}); this is the maximum stock density allowed by the German guidelines for organic farming. It might have been expected that in the phase of intensification N losses would rise sharply. However, under the existing site and management conditions, additionally available nitrogen was fixed in the biomass or stored as SON. It is surprising that N losses determined in the soil surface balance (Table 5) derived from changes in SON stock did not increase but fell even to a minimum in 2001/2002. Comparable results were communicated also by Knudsen et al. (2006), who computed rising SON stocks and declining N loss in different cropping systems in Denmark with rising organic fertilisation. Christensen and Johnston (1997) observed that incorporating straw enhances the stock of soil N and reduces N losses but not to the same extent as does FYM application.

In the conventional system, N utilisation has substantially improved in recent years. N surpluses decreased to <50 kg N ha^{-1} yr^{-1}, and in 2005/2006 N utilisation exceeded even the level of the organic system (Table 6). It proved possible to reduce N losses down to the level of organic farming by best management practice in conventional farming.

In Scheyern this might be attributed to lower N inputs (ending slurry purchase without compensation from higher doses of mineral N) accompanied by higher N outputs. The rise in N removal was an effect of improved management (intensive plant protection measures, improved tillage, higher yielding varieties). Simultaneously, however, SON values were decreasing, and therefore the development cannot be described as fully sustainable.

5. Conclusions

N balancing tools have become widely used by scientists, policy-makers, consultants and farmers as useful instruments for planning and control of on-farm nitrogen management. Within Europe, several N balance tools have been developed, which differ mainly in where the system boundary is drawn, which spatial and temporal resolutions can be achieved and which inputs and outputs are taken into consideration. Simple approaches often neglect farm internal pools and flows of nitrogen. They are mostly used for comparative analyses of management systems. However, if special emphasis is to be given to system analysis and optimisation, farm internal structures and processes have to be moved into the focus of attention. An analysis of mass flux relationships facilitates the comprehensive understanding of a system. Therefore, our model integrates the method of system balancing, which combines partial balances, i.e. farm gate balance, stable balance and soil surface balance, in order to reflect all relevant mass fluxes between the subsystems soil–plant–animal–environment. Such a system approach reveals the causes of N utilisation differences and is the precondition for scenario calculations aimed at reducing N losses.

Beside the total farm scale, N utilisation and N loss may also be rated at the level of crop rotation. There is a continuous N transfer within a crop rotation via the soil as nitrogen store, for example from legumes to non-legumes or as long-term effects of organic fertiliser. A single year analysis of crops may be misleading because of possibly high N surplus or N deficiencies that do not reflect the actual N loss potentials; only integration on crop rotation level produces reliable N balances (Tables 1 and 2). Thus, it is essential to analyse sufficiently long periods, preferably complete crop rotations, to avoid misinterpretations.

Case studies in farms, as in the experimental station Scheyern, represent a valuable and necessary supplement to factorial field experiments. A decisive advantage vis-à-vis field experiments is the complete and realistic description of farm internal mass fluxes in the system soil–plant–animal–environment. The only situation in which farming systems achieve a steady state as a result of constant management conditions is in long-term field experiments. Disturbances of a farming system, as simulated in Scheyern by intensification and extensification periods, are no exception but rather the norm. So, matching experimental farming systems to real farm conditions, as was done here in Scheyern, composites for the limitations it places on statistical analysis.

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