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ORIGINAL ARTICLE

Nitrogen balances and nitrogen-use efficiency of different organic and conventional farming systems

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Abstract Nitrogen (N) is the most important yield-limiting factor in agricultural systems, however, N application can lead to emissions and environmental problems such as global warming (N_2O) and groundwater contamination (NO_3^-). This study analyses the N balance, nitrogen-use efficiency, and N loss potential of conventional farming systems (arable farming, improved arable farming, and agroforestry) and organic farming systems (mixed farming, arable farming, and agroforestry) based on long-term field experiments in southern Germany. The effects of the conversion of farm structure and N management are identified. The conventional farming systems in this study were high N-input and high N-output systems. The conventional arable farming system had the lowest nitrogen-use efficiency and the highest N surplus. An optimised N management and the use of high-yielding crop varieties improved its nitrogen-use efficiency. The establishment of conventional agroforestry resulted in the reduction of N input, N output and N surplus, while maintaining high yields. The organic mixed farming system is characterised by a relatively high N input and N output, the accumulation of soil organic nitrogen, the highest nitrogen-use efficiency, and the lowest N surplus of all analysed systems. These good results can be attributed to the intensive farm N cycle between soil–plant–animal. The shift from organic mixed farming to organic arable farming system extensified the N cycle, reduced N input, crop yield and N output. The change from organic arable farming to organic agroforestry reduced the N input, increased the biomass yield, and remained the N surplus within an optimal range.

Keywords Nitrogen balance · Nitrogen-use efficiency · Organic farming · Conventional farming · Agroforestry

Highlights

1. A comprehensive N balance method was adapted to agroforestry systems.
2. We quantify the effects of changing farm structures on the nitrogen-use efficiency.

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3. Organic mixed farming has the highest nitrogen-use efficiency of all farming systems.
4. Agroforestry can improve nitrogen-use efficiency and reduce N surpluses.

Introduction

Nitrogen (N) is the most important yield-limiting factor in agricultural systems (Tilman 1999). It is mainly supplied by mineral fertilisers, farm manure, symbiotic N_2 fixation, and atmospheric wet and dry deposition. Stewart et al. (2005) reported that at least 30–50 % of the crop yield is attributed to the application of mineral fertiliser. However, when the applied N is not completely taken up by plants nor accumulated as soil organic N (SON), it results in emissions and associated environmental problems such as global warming (N_2O), groundwater contamination (NO_3^-), air pollution and eutrophication (NH_3), and loss of biodiversity (Crutzen et al. 2008; European Environmental Bureau 2013; Ju et al. 2006; Millar et al. 2010; Sutton et al. 2011b). A recent study pointed out that the threats posed by N emissions cost the European Union more than double the value which N fertiliser adds to European farm income (Sutton et al. 2011a, b). The high energy consumption and greenhouse gas emissions generated by the production and use of mineral fertiliser (Dawson and Hilton 2011; Hülsbergen et al. 2001; Snyder et al. 2009) are also threats to the environment and society.

N-management and N-balance in conventional and organic farming

Both high N-input systems (e.g. conventional farming) and low N-input systems (e.g. organic farming) are found in Western Europe. Spiertz (2010) suggested that the focus in high N-input systems should be to improve the efficiency of applied N (more yield with less fertiliser N), while in low-input systems additional N input is required to increase yield level and yield stability. In Germany, the high N input and N surplus of conventional farms are mainly from the use of high doses of mineral N, often in combination with organic N (e.g. slurry, biogas slurry). The mean N surplus of Germany at farm-gate scale is about 100 kg N ha^{-1} yr^{-1} (Taube et al. 2013; Umweltbundesamt 2014). However, whether a significant reduction of N surplus without negative yield effects is possible has not been studied comprehensively.

The most important N sources in organic farming are green and animal manure and symbiotic N_2 fixation. These N sources can be combined in mixed farming systems perfectly: N-fixing crops (e.g. clover and alfalfa) could be harvested as fodder for animals, and the animal manure will be returned to the soil as an N source, therefore the N cycle is nearly closed and N losses are minimised (Küstermann et al. 2010). However, current policies and economic benefits encourage European farmers to enlarge and specialise their farms (Ryschawy et al. 2012) and consequently reduce the amount of both organic and conventional mixed farms. According to a survey done in the agrarian region north of Munich, southern Germany, 40 % of the organic farms are managed as specialised arable farming systems (AF) (Vockinger 2013) and this number is still increasing. However, this change may affect the farm's nitrogen cycle, soil fertility, and yield potential (Van Keulen and Schiere 2004). The long-term effects of the shift from organic mixed farming to specialised organic arable farming systems are so far not being looked into, therefore leaves a research gap in this field.

N-management and N-balance of agroforestry systems

Agroforestry systems (AGFS) are multifunctional land use systems with trees incorporated into agricultural crop and/or animal production. The interaction between woody and non-woody components benefits these systems economically, ecologically, environmentally and socially (Jose 2009; Reynolds et al. 2007).

The combination of short-rotation trees for energy wood production and agricultural crops is one of the modern forms of AGFS gaining most of the interest in Germany (Johann-Heinrich von Thünen-Institut 2012; Nerlich et al. 2013). Even though this farming system is still not widespread in Germany, the establishment of AGFS could help to reduce the N surplus and N emissions of farming systems because (1) the N demand of short-rotation trees is generally less than that of agricultural crops (Dawson 2007; Musshoff 2012; Sevel et al. 2014), thus the external N inputs as well as the N surplus of the whole AGFS system can be reduced, and (2) it has the potential to optimise the nitrogen-use efficiency (NUE) of the system due to its ability to enhance soil quality and nutrient uptake (Bambrick et al. 2010; Ilany et al. 2010; Isaac et al. 2007; Patra 2013). However, the effects on yields, nitrogen-use efficiency, and soil fertility of N-limited organic farms through the establishment of AGFS have not yet been analysed to the authors' best knowledge.

Study scope

Scheyern Research Farm in southern Germany has been established with different conventional and organic farming systems. Thus, the analysis and comparison of the NUE and nitrogen surplus from different N management strategies under the same soil and climate conditions is possible, using a unique long-term data set (Fig. 1). This article is based on (1) data collected from the organic mixed farming system and conventional arable farming system between 1999 and 2002 (partly been reported by Küstermann et al. 2010, see Tables 1 and 4), and (2) data collected from the organic and conventional arable farming and agroforestry systems from 2009 to 2012 (the results from the first stage of a 20-year long-term agroforestry experiment). Therefore, the effects of the change from organic mixed farming to organic arable farming and organic agroforestry, as well as from conventional arable farming to conventional agroforestry, could be analysed.

This study determines the NUE of the above-mentioned organic and conventional farming systems by analysing N input, N uptake, N output, accumulation or depletion of soil organic nitrogen (Δ SON), and N surplus. The aims of this study are (1) improving a comprehensive N balance method (Küstermann et al. 2010) in order to make it applicable to mixed farming, arable farming, and agroforestry systems; (2) analysing the effects of changing farm structures and nitrogen management, and identifying the systems with the highest N output, highest NUE, and the lowest N loss potential; and (3) examining whether it is possible to increase the DM yield, optimise the NUE, sustain soil fertility, and reduce N surplus at the same time.

Methodology

Experimental site

The experimental data analysed in this study was collected at the Scheyern Research Farm, 40 km north of Munich in southern Germany. The research farm is located at 445–498 m above sea level in a hilly landscape with soils characterised as loamy to sandy cambisols derived from tertiary sediments partly covered by loess (Schröder et al. 2002). The mean annual precipitation and temperature is 887 mm and 8.3 °C, respectively (Wetterdienst 2012).

The experimental farm was established with an organic mixed farming system (31.3 ha arable fields with crop rotation and 18.2 ha permanent grassland) and a conventional arable farming system (30.4 ha

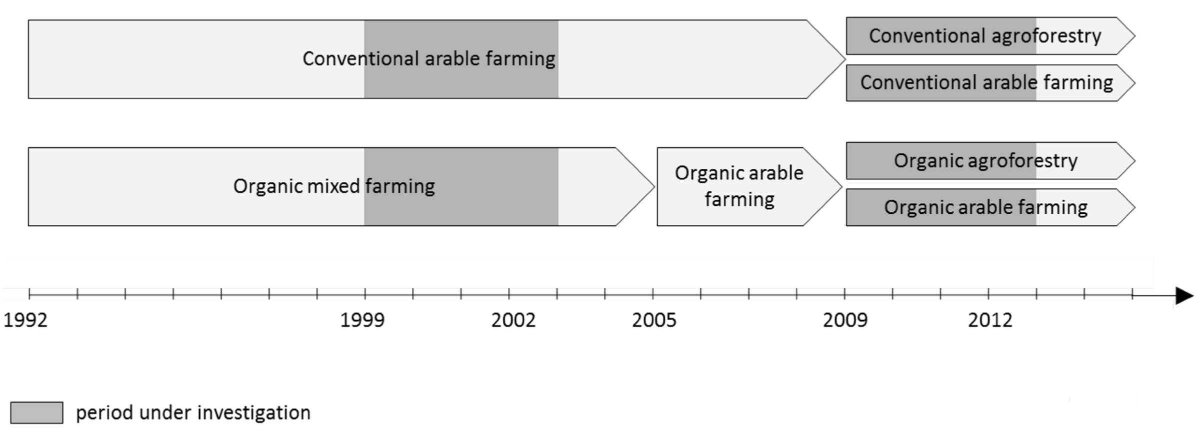

Fig. 1 The development of farming systems in Scheyern Research Farm

Table 1 Nitrogen soil surface balance of the conventional crop rotation, averaging the years 1999–2002

Field	Crop	Mineral N[a] (kg N ha^{-1})	Slurry[a] (kg N ha^{-1})	N input[b] (kg N ha^{-1})	Biomass: Yield[a,c] (Mg DM ha^{-1})	Biomass: Straw/green manure[d] (Mg DM ha^{-1})	N uptake[e] (kg N ha^{-1})	Straw/green manure[a,c] (kg N ha^{-1})	N output[a] (kg N ha^{-1})	Δ SON (kg N ha^{-1})	N surplus: With Δ SON (kg N ha^{-1})	N surplus: Without Δ SON[a] (kg N ha^{-1})	NUE With/without[a] Δ SON
1	Potato	90		106	8.9	6.2	203	75	128	−89	67	−22	0.72/1.02
	+ catch crop mustard	20		20		4.2	127	127		36	−16	20	
2	Winter wheat	160	46	222	5.9	4.7	172	28	144	−2	79	78	0.64/0.65
3	Forage maize	130	58	204	13.8		178		178	−69	95	26	0.69/0.79
	+ catch crop mustard	20		20		4.2	127	127		36	−16	20	
4	Winter wheat	160	28	204	5.5	4.4	179	30	149	−7	61	55	0.71/0.73
	Crop rotation	145	33	194	8.5	6.0	247	97	150	−24	68	44	0.69/0.79

Data were from Küstermann et al. (2010) and their unpublished work

[a] Data reported by Küstermann et al. (2010)

[b] N input = Mineral N + Farm Yard Manure (FYM) + Slurry + N deposition (ave. 16 kg N ha^{-1} yr^{-1})

[c] Harvested products

[d] Unharvested products (straw of winter wheat and winter rye, catch crop mustard, unharvested biomass of potato)

[e] N uptake = N contained in the aboveground crop biomass

arable fields with crop rotation) in 1992 (Küstermann et al. 2010).

In the organic mixed farming system, a suckler cow herd was kept. The stock density had increased gradually from 0 livestock units ha^{-1} (in 1992) to 1.4 livestock units ha^{-1} (averaged from 1999 to 2002). 1999–2002 was the period with the highest production intensity (highest livestock density, highest N input) (Küstermann et al. 2010). The stock numbers of the organic mixed farming system were reduced in 2005, in order to simulate changes brought by the shift to a specialised arable farming system.

The organic rotation comprises: (1) grass-clover-alfalfa (GCA, *Lolium perenne* L. + *Trifolium pretense* L. + *Medicago sativa* L.), (2) potato (*Solanum tuberosum* L.) + catch crop mustard (*Sinapis alba* L.) or catch crop Egyptian clover (*Trifolium alexandrinum* L.) and bean (*Vicia faba* L.), (3) winter wheat (*Triticum aestivum* L.), (4) sunflower (*Helianthus annuus* L.) + undersown GCA, (5) GCA, (6) winter wheat, and (7) winter rye (*Secale cereale* L.) + undersown GCA, with a complete duration of 7 years. GCA was harvested as fodder during 1999–2002, but used as green manure during 2009–2012.

The conventional crop rotation includes: (1) forage maize (*Zea mays* L.) + catch crop mustard, (2) winter wheat, (3) potato + catch crop mustard, and (4) winter wheat. The cultivation of catch crops (mustard or clover) varied slightly from year to year, depending on the soil and management conditions. Compared to the period 1999–2002, the management in 2009–2012 was improved by better adaption of N fertiliser input to the N demand of the crops, and by using new crop varieties with higher yield potential.

The agroforestry systems were established in 2009 as long-term experiments on four fields (two with organic, two with conventional farming). They are a combination of strips of short rotation trees for bioenergy production (T_{AGFS}, 22 % of AGFS area) and of crop area for arable farming for food production (C_{AGFS}, 78 % of AGFS area). The investigated tree species were poplar (*Populus maximowiczii* × *P. nigra*), willow (*Salix triandra* x *S. viminalis*), black locust (*Robinia pseudoacacia*), and black alder (*Alnus glutinosa*). The agroforestry experiments were designed with a 4-year growing period for trees, and a total experimental period of 20 years. Further information on the design of the field experiment can be found in Lin et al.

Nitrogen balance and NUE

The N balance and the NUE were computed for the crop subsystem (soil surface balance), the animal subsystem (barn balance), and the whole farm (farm-gate balance) for the period 1999–2002. These balances can be combined into a system balance, and thus allows the quantification of all relevant N fluxes. From 2009 to 2012, no animal subsystem was involved in the farming systems and thus, the N balance was computed only for the plant (crop and tree) subsystem and the whole farm.

The modelling approach used in this study was described in Küstermann et al. (2010). In this study, we derivate N balance parameters for tree subsystems in agroforestry based on experimental data and parameter from literature (e.g. specific N contents of tree biomass to estimate the N output; N contents of leafs to calculate the N uptake). We integrate a method to calculate symbiotic N_2 fixation of trees (black locust, black alder) as well as an approach to estimate SON-accumulation of trees. So the approach of Küstermann et al. (2010) was expanded and can be used in agroforestry systems with different tree species.

Parameters in this study were N input, N uptake, N output, Δ SON, NUE, and N surplus. The N input included the N fluxes from symbiotic N_2 fixation, mineral N, slurry, farmyard manure, and N deposition. N in seed/seedlings was not included because it is of minor importance regarding environmental issues. The N uptake was defined as the nitrogen contained in the whole aboveground crop/tree biomass, whereas N output considered only the nitrogen contained in the harvested products. NUE was defined as N output in relation to N input. It was analysed with and without the consideration of Δ SON:

$$\text{NUE (without } \Delta \text{ SON)} = \sum \text{N output} \times \left(\sum \text{N input}\right)^{-1} \quad (1)$$

$$\text{NUE (with } \Delta \text{ SON)} = \sum \text{N output} \times \left(\sum \text{N input} - \text{SON}\right)^{-1} \quad (2)$$

The parameter Δ SON was included in the N balance to quantify NUE and N surplus (N loss potential) more precisely (Küstermann et al. 2010).

N surplus, which represents the potential N loss by the system, was defined as the difference between N input and N output. It was also analysed with and without the consideration of Δ SON:

$$\text{N surplus (without } \Delta \text{ SON)} = \sum \text{N input} - \sum \text{N output} \quad (3)$$

$$\text{N surplus (with } \Delta \text{ SON)} = \sum \text{N input} - \Delta \text{ SON} - \sum \text{N output} \quad (4)$$

The N content of farming products and harvested wood was taken from Hülsbergen (2003), Seidl et al. (2014), and experimental data.

Symbiotic N_2 fixation is an important N source for the tree strips and organic crop rotation in this study. The methods for calculating the symbiotic N_2 fixation of legume crops and trees are described below.

Symbiotic N_2 fixation of legume crops

The symbiotic N_2 fixation of legume crops was calculated based on the assumption that (1) N_2 fixation increases with increasing yield (Carlsson and Huss-Danell 2003; Høgh-Jensen et al. 2004) and (2) the N fixed by crops contributes to a specific share of N uptake. The equations were presented by Küstermann et al. (2010) as:

$$NY_{sym} = Y \times DM \times 0.01 \times N \times L \times 0.01 \times \%\ N_{dfa} \times 0.01 \quad (5)$$

where NY_{sym} = symbiotically fixed nitrogen in the yield (kg N ha^{-1} yr^{-1}), Y = fresh matter yield (kg ha^{-1} yr^{-1}), DM = dry matter content (%), N = N content in dry matter (kg N kg^{-1} DM), L = share of legumes among the plants (%) and $\%N_{dfa}$ = proportion of nitrogen derived from atmosphere (differentiated according to cropping conditions and the content of plant-available N in the soil) (%).

$$NR_{sym} = NY_{sym} \times r_{DM} \times r_N \quad (6)$$

where NR_{sym} = symbiotically fixed nitrogen in crop residues (kg N ha^{-1} yr^{-1}), r_{DM} = DM residues/DM yield and r_N = N content residues/N content yield

Symbiotic N_2 fixation by trees

We used mean $\%N_{dfa}$ values of locust and alder to determine the amount of symbiotic N_2 fixation. The equation was expressed as:

$$NT_{sym} = (N_h + N_l + N_r) \times \%\ N_{dfa} \times 0.01 \quad (7)$$

where NT_{sym} = symbiotically fixed nitrogen in the whole tree (wood, roots, and leaves) (kg N ha^{-1} yr^{-1}), N_h = N in harvested woody biomass (= N output of trees) (kg ha^{-1} yr^{-1}), N_l = N in leaf litter (kg ha^{-1} yr^{-1}) and N_r = N in roots (kg ha^{-1} yr^{-1}).

The parameters N_h and N_l were measured, and N_r was derived from the ratio of N_r to N_h (Uri et al. 2011). The mean value of $\%N_{dfa}$ of black alder and black locust in Germany is 70 %, however, it ranges from 60 to 80 % (Dittert 1992; Veste et al. 2013). Due to the good soil quality and nitrogen availability of the experimental sites, we used 60 % as the $\%N_{dfa}$ of black alder and black locust in this study.

Nitrogen in tree leaves was not part of the N output in the N balance because it was recycled in litterfall to the soil. Thus, it is presented in the N balance as N uptake and N in green manure.

Soil organic nitrogen

Soil organic N depletion or accumulation (Δ SON) in crop areas was calculated based on the algorithm of the model REPRO (Hülsbergen 2003; Küstermann et al. 2010). This method considered the specific effects of crops (depending on site, yield, and mineral N doses) and organic fertilisers (depending on quality and quantity) on the organic nitrogen pool of the soil, with parameters derived in long-term field experiments with various crop rotations and fertilization patterns in regions of different soil and climate conditions for more than 20 years (Küstermann et al. 2008). The Δ SON of T_{AGFS} area was assumed to be 0 kg N ha^{-1} yr^{-1} for trees not fixing N (Petzold et al. 2010) and 30 % of the fixed N for N-fixing trees (Dulormne et al. 2003).

For the sake of clarity, only the main N fluxes are shown in our tables and figures.

Results

Nitrogen soil surface balance of the conventional farming systems

From 1999 to 2002, the N supply in the conventional arable farming system ($AF_{1999–2002}$) was mainly from mineral fertiliser (75 % of the N input) (Table 1). The mean N output in the harvested biomass (150 kg ha^{-1}) was 61 % of the N uptake. Forage maize had the highest DM yield (13.8 Mg ha^{-1}), and thus the highest N output (178 kg ha^{-1}) as the whole plant was harvested (uptake = output). Potato had the highest aboveground crop biomass and N uptake, but 37 % of the N was returned to the soil in the form of potato residues. However, its N output was still higher than the N supply, resulting in a negative N surplus without considering Δ SON. In winter wheat the N input was high, but, although N uptake was of a comparable order of magnitude to maize, N output was relatively low. Therefore, the N surplus in winter wheat was the highest among the crops. The highest SON depletion occurred during the cultivation of potato and forage maize, however, the catch crop mustard had a positive effect on SON (green manure). For the crop rotation, a decline of the SON (−24 kg N ha^{-1} yr^{-1}) was computed. Taking Δ SON into account increases the N surplus from 44 to 68 kg ha^{-1}, which decreases the NUE from 0.79 to 0.69.

From 2009 to 2012, the N input in the conventional arable farming system ($AF_{2009–2012}$) was similar to that of $AF_{1999–2002}$. The mineral N input (+23 %) was adapted to the higher yield potential and N uptake of new crop varieties (forage maize and wheat), and to compensate for the reduction in other N inputs (no slurry application). The DM yield increased by 18 % in conventional $AF_{2009–2012}$, mainly due to the improved yield of forage maize (+36 %). Maize was also the crop which removed the most N from the system. Because of the higher DM yield, the N output of conventional $AF_{2009–2012}$ was higher than that of conventional $AF_{1999-2002}$ (+15 %). As a result, the N surplus of conventional $AF_{2009–2012}$ was lower and the NUE improved compared to the reference period.

The lower yield and N uptake of catch crop mustard (after forage maize) in conventional $AF_{2009–2012}$ was the result of the later harvest time of forage maize due to the type of cultivar and the weather conditions in this period. Compared to $AF_{1999–2002}$, the modelled SON depletion was higher, which can be partly explained by the reduced input of green manure and no slurry application.

When comparing conventional $AF_{2009–2012}$ and the conventional C_{AGFS} $area_{2009–2012}$ in the agroforestry system, the management and DM yields differed only slightly according to the soil characteristics, tree-crop interactions, and different management conditions (e.g. smaller field sizes in AGFS). The N surplus and the nitrogen-use efficiency of the C_{AGFS} $area_{2009–2012}$ are similar to the N surplus and NUE of $AF_{2009–2012}$ (see Tables 2, 3).

The T_{AGFS} area in conventional AGFS was a low-N-input (60 kg N ha^{-1} yr^{-1}) and low-N-output (46 kg N ha^{-1} yr^{-1}) system, although we measured relatively high N contents of the wood biomass (0.62–0.70 % N in DM) due to young plant material with a high amount of bark. The N surplus of T_{AGFS} area was 14 kg N ha^{-1} yr^{-1}. However, when taking Δ SON into consideration, the N surplus became 1 kg N ha^{-1} yr^{-1}, which was much lower than that of the conventional C_{AGFS} area. When the N stored in roots (19 kg N ha^{-1} yr^{-1}, not shown in Table 3) was also considered, the N surplus decreased to −18 kg N ha^{-1} yr^{-1}.

The tree species poplar and willow had a high NUE (2.87 and 1.12, respectively) and a negative N surplus (−30 and −2 kg N ha^{-1} yr^{-1}, respectively) (both with and without Δ SON, Table 3) due to the low N input. The N_2-fixing tree species black alder and black locust had higher N inputs compared to poplar and willow. The calculated N_2 fixation amounted to more than 80 kg N ha^{-1} yr^{-1}. Therefore, the NUE of black alder and black locust was considerably lower and N surplus was discernibly higher. The establishment of tree strips resulted in a 15 % lower N input in conventional AGFS, reduced the depletion of SON, and reduced the N surplus of the whole system compared to conventional $AF_{2009–2012}$. However, there was no substantial effect on the NUE.

Nitrogen soil surface balance of the organic farming systems

During the period 1999–2002, the main N sources in the organic crop rotation were the symbiotic N_2 fixation from grass-clover-alfalfa (47 %), and farmyard manure and slurry from animal husbandry (44 %)

Table 2 Nitrogen soil surface balance of the conventional crop rotation, arable farming, averaging the years 2009 to 2012

Field	Crop	Mineral N	N input[a]	Biomass		N uptake[d]	Straw/green manure[c]	N output	Δ SON	N surplus		NUE
				Yield[b]	Straw/green manure[c]					With Δ SON	Without Δ SON	With/without Δ SON
		(kg N ha^{-1})	(kg N ha^{-1})	(Mg DM ha^{-1})	(Mg DM ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	
1	Potato	130	146	8.8	6.2	201	75	127	−58	77	19	0.62/0.87
2	Winter wheat	192	208	6.5	5.2	190	31	159	−2	51	50	0.76/0.76
3	Forage maize	197	213	18.8		243		243	−83	53	−30	0.87/1.14
	+catch crop mustard	0	0		1.5	45	45		17	−17	0	
4	Winter wheat	195	211	6.1	4.9	195	29	165	−5	51	46	0.77/0.78
	Crop rotation	179	195	10.0	4.4	218	45	173	−33	54	21	0.76/0.89

[a] N input = Mineral N + N_2 Fixation + N deposition (ave. 16 kg N ha^{-1} yr^{-1})

[b] Harvested products

[c] Unharvested products (straw of winter wheat and winter rye, green manure of mustard, unharvested biomass of potato)

[d] N uptake = N contained in the aboveground crop biomass

Table 3 Nitrogen soil surface balance of the conventional crop rotation, agroforestry, averaging the years 2009 to 2012

Field	Crop	Mineral N	N_2 Fixation	N input[a]	Biomass		N uptake[d]	Straw/green manure[c]	N output	Δ SON	N surplus		NUE
					Yield[b]	Straw/green manure/leaf litter[c]					With Δ SON	Without Δ SON	With/without Δ SON
		(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(Mg DM ha^{-1})	(Mg DM ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	
1	Potato	130		146	10.6	7.4	242	90	153	−92	85	−7	0.64/1.05
2	Winter wheat	192		208	6.1	4.9	178	29	149	−1	60	59	0.71/0.71
3	Forage maize	197		213	17.6		227		227	−67	53	−14	0.86/1.07
	+catch crop mustard			0		1.5	45	45		17	−17	0	
4	Winter wheat	195		211	5.9	4.7	188	28	160	−4	55	51	0.74/0.76
	Crop rotation	179		195	10.1	4.6	220	48	172	−37	59	22	0.74/0.88
	Poplar		0	16	8.5	4.9	100	54	46	0	−30	−30	2.87/2.87
	Willow		0	16	3.9	1.2	41	23	18	0	−2	−2	1.12/1.12
	Alder		88	104	7.6	2.8	122	70	52	26	26	52	0.67/0.50
	Locust		86	102	9.7	3.4	120	52	68	26	9	35	0.89/0.66
	Tree strips	0	44	60	7.4	3.1	96	50	46	13	1	14	0.99/0.77
	AGFS	140	9	165	9.5	4.3	193	49	145	−26	47	21	0.76/0.88

[a] N input = Mineral N + N_2 Fixation + N deposition (ave. 16 kg N ha^{-1} yr^{-1})

[b] Harvested products

[c] Unharvested products (straw of winter wheat and winter rye, green manure of mustard, unharvested biomass of potato) and leaf litter of trees

[d] N uptake = N contained in the aboveground crop biomass

Table 4 Nitrogen soil surface balance of the organic crop rotation, averaging the years 1999 to 2002

Field	Crop	N_2 fixation[a] (kg N ha^{-1})	FYM, Slurry[a] (kg N ha^{-1})	N input[b] (kg N ha^{-1})	Biomass: Yield[a,c] MP (BP) (Mg DM ha^{-1})	Biomass: Straw/green manure[d] (Mg DM ha^{-1})	N uptake[e] (kg N ha^{-1})	Straw/green manure[a,d] (kg N ha^{-1})	N output[a] (kg N ha^{-1})	Δ SON (kg N ha^{-1})	N surplus: With Δ SON (kg N ha^{-1})	N surplus: Without Δ SON[a] (kg N ha^{-1})	NUE: With/without[a] Δ SON
1	GCA	261		277	11.8		304		304	95	−122	−27	1.67/1.10
2	Potato		186	202	4.9	3.4	97	31	66	18	118	136	0.40/0.33
	+undersown mustard					1.9	46	46		21	−21		
3	Winter wheat		117	133	2.4 (2.2)		59		59	7	68	74	0.47/0.44
4	Sunflower		90	106	1.6	1.6	85	39	46	−29	89	60	0.66/0.34
	+undersown GCA	31		31		1.8	46	46		65	−34	31	
5	GCA	*236*		252	10.9		283		283	96	−127	−31	1.81/1.12
6	Winter wheat		49	65	3.1 (2.8)		82		82	−58	41	−17	0.67/1.26
7	Winter rye		112	128	2.9 (2.9)		64		64	−6	70	64	0.70/0.79
	+undersown GCA	50		50	2.9		76		76	42	−68	−26	
	Crop rotation	83	79	178	5.8 (1.1)	1.2	163	23	140	35	3	38	0.98/0.77
	Grassland[f]	33	105	154	6.2	0	136	0	136	0	18	18	0.88/0.88
	Agricultural land	60	91	167	6.6	0.8	151	13	138	20	9	29	0.94/0.82

Data were from Küstermann et al. (2010) and their unpublished work

[a] Data reported by Küstermann et al. (2010)

[b] N input = N_2 Fixation + Farm Yard Manure (FYM) + Slurry + N deposition (ave. 16 kg N ha^{-1} yr^{-1})

[c] Harvested products, MP = main products, (BP) = by-products (straw of winter wheat and winter rye)

[d] Unharvested products (unharvested biomass of potato, sunflower, undersown mustard, and undersown GCA of sunflower)

[e] N uptake = N contained in the aboveground crop biomass

[f] Mixed organic farm with 31.3 ha arable land (crop rotation), 18.2 ha permanent grassland

(Table 4). The relatively high N output of the crop rotation (140 kg N ha^{-1} yr^{-1}) resulted mainly from the high-yielding grass-clover-alfalfa. GCA was also the crop with the highest N uptake, contributed the highest amount of SON accumulation, but had also a negative N balance. The whole crop rotation brought a SON accumulation of 35 kg ha^{-1} yr^{-1}, a N surplus of 38 kg ha^{-1} yr^{-1} without and 3 kg ha^{-1} yr^{-1} with Δ SON, and a NUE of 0.77 without and 0.98 with Δ SON.

There was no application of FYM and slurry in the organic arable farming system between 2009 and 2012 after the shift from mixed farming to cash crop production. There was also no harvest of GCA (used as green manure) under this new management system. The N input of the organic AF was only 41 % of the N input in the crop rotation of the organic mixed farming system (Table 5). The lower N input and harvest index (DM yield/biomass production; organic AF: 0.30, organic mixed farming: 0.85,) resulted in a very low DM yield, as well as in an extremely low N output. The Δ SON of organic AF was 11 kg N ha^{-1} yr^{-1}. The N surplus (8 kg N ha^{-1} yr^{-1}, with Δ SON) stayed at the same level as during the organic mixed farming period. The NUE of organic AF was lower than that of the organic mixed farming system.

GCA was the crop with the highest N uptake and the highest SON accumulation in organic AF. The N_2 fixation, N uptake, and SON accumulation of mulched GCA differed from the harvested GCA in the organic mixed farming system as a result of different DM yields, proportion of legumes in the mixture, and $\%N_{dfa}$ rate caused by specific conditions and management. The nitrogen fixed by GCA was partly accumulated in soil organic nitrogen and transferred to the other crops in the crop rotation after mineralization. The N surplus of GCA in organic AF was positive as the biomass was not removed from the system. Wheat after GCA had the highest N output, and sunflower the highest N surplus in organic AF.

The management, DM yields, and N balance of organic AF and the organic C_{AGFS} area (2009–2012) (Table 6) differed slightly, but both were low-N-input and low-N-output systems.

In the T_{AGFS} area of organic AGFS, poplar and willow had higher NUE (4.22 and 2.68, respectively) and lower N surplus (−52 and −27 kg N ha^{-1} yr^{-1}, respectively) compared to N_2-fixing black alder and black locust. Due to the higher tree yields of poplar and willow in the organic T_{AGFS} area, the NUE of the whole organic T_{AGFS} area was higher than the NUE of the conventional system.

Nitrogen cycle of organic mixed farming, organic arable farming, organic agroforestry, and conventional agroforestry systems

Because of the different structure and subsystems, the N fluxes and N pools of the analysed farming systems were very different.

Figure 2 shows the N cycle of the organic mixed farming system (1999–2002). There were two kinds of N input: for crops (e.g. N_2 fixation) and for animals (e.g. forage and straw). Nitrogen left the system via cash products (crops: 28 kg N ha^{-1}, animals: 22 kg N ha^{-1}) and various N losses. The greatest part (78 %) of the N in the harvested products from the crop area entered the animal subsystem as forage, was returned partly to the soil as FYM and slurry, and was taken up by the crops again. The input of forage and straw into the animal subsystem and the repeated use of N intensified the farm internal N cycle of the organic mixed farming system. In total, 69 % of the N uptake by plants was returned to the soil as manure. When the system boundary was expanded to the farm gate, the NUE of the organic mixed farming system was 0.47, and the N surplus 60 kg N ha^{-1} yr^{-1}.

The N cycle of the organic arable farming system was simpler than that of the organic mixed farming system (Fig. 3). Furthermore, the N form, N availability, and N yield effects were different. There was an important N transfer from GCA to the other crops in the organic AF, so that its DM yield was sustained at a certain level without extra N input. At the farm-gate level, the NUE of the organic AF amounted to 0.74, and the N surplus amounted to 8/19 kg N ha^{-1} (with/without ΔSON).

The N cycle of the organic C_{AGFS} area was similar to the organic AF (Fig. 4). The N input of the organic T_{AGFS} area (mean value of the analysed tree species) was lower than the N input of the organic C_{AGFS} area due to the smaller amount of N_2 fixation. The N uptake and N in plant residues (leaf litter) were less than those of the C_{AGFS} area. The N output via the harvest of aboveground woody biomass (55 kg N ha^{-1} yr^{-1}) was similar to the N output of the C_{AGFS} area. The ratio of N taken up to N returned to soil in the C_{AGFS} area, T_{AGFS} area and the whole AGFS system was 68, 49

Table 5 Nitrogen soil surface balance of the organic crop rotation, arable farming, averaging the years 2009 to 2012

Field	Crop	N_2 fixation	N input[a]	Biomass		N uptake[d]	Straw/green manure[c]	N output	Δ SON	N surplus		NUE
				Yield[b]	Straw/green manure[c]					With Δ SON	Without Δ SON	With/without Δ SON
		(kg N ha^{-1})	(kg N ha^{-1})	(Mg DM ha^{-1})	(Mg DM ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	
1	GCA	144	160		10.0	260	260		147	14	160	
2	Potato		16	6.0	4.2	119	38	81	−84	19	−65	0.81/5.06
3	Winter wheat		16	2.6	2.3	74	11	64	−42	−6	−48	1.10/4.00
	+catch crop Egyptian clover and bean	90	90		4.0	72	72		88	2	90	
4	Sunflower		16	2.6	2.6	138	63	75	−109	50	−59	0.60/4.68
	+undersown GCA	22	22		2.0	52	52		44	−22	22	
5	GCA	144	160		10.0	260	260		147	14	160	
6	Winter wheat		16	3.4	3.1	104	14	90	−65	−9	−74	1.11/5.63
7	Winter rye		16	3.1	3.1	82	14	69	−47	−6	−53	1.09/4.28
	Crop rotation	57	73	2.5	5.9	166	112	54	11	8	19	0.87/0.74

[a] N input = N_2 Fixation + N in seed + N deposition (ave. 16 kg N ha^{-1} yr^{-1})

[b] Harvested products

[c] Unharvested products (straw of winter wheat and winter rye, green manure of GCA, unharvested biomass of potato, sunflower)

[d] N uptake = N contained in the aboveground crop biomass

Table 6 Nitrogen soil surface balance of the organic crop rotation, agroforestry, averaging the years 2009 to 2012

Field	Crop	N_2 fixation (kg N ha^{-1})	N input[a] (kg N ha^{-1})	Biomass: Yield[b] (Mg DM ha^{-1})	Biomass: Straw/green manure/leaf litter[c] (Mg DM ha^{-1})	N uptake[d] (kg N ha^{-1})	Straw/green manure[c] (kg N ha^{-1})	N output (kg N ha^{-1})	Δ SON (kg N ha^{-1})	N surplus: With Δ SON (kg N ha^{-1})	N surplus: Without Δ SON (kg N ha^{-1})	NUE With/without Δ SON
1	GCA	144	160		10.0	260	260		147	14	160	
2	Potato		16	6.9	4.8	137	44	93	−99	21	−77	0.81/5.82
3	Winter wheat		16	2.8	2.5	80	11	69	−46	−7	−53	1.11/4.31
	+catch crop Egyptian clover and bean	90	90		4.0	72	72		88	2	90	
4	Sunflower		16	2.7	2.7	144	66	78	−114	5	−62	0.60/4.86
	+undersown GCA	22	22		2.0	52	52		44	−22	22	
5	GCA	144	160		10.0	260	260		147	14	160	
6	Winter wheat		16	2.9	2.6	89	12	77	−54	−7	−61	1.10/4.08
7	Winter rye		16	2.6	2.6	69	12	57	−37	−4	−41	1.08/3.59
	Crop rotation	57	73	2.6	5.9	166	113	53	11	9	20	0.86/0.73
	Poplar		16	10.9	4.9	122	55	68	0	−52	−52	4.22/4.22
	Willow		16	6.4	1.1	65	22	43	0	−27	−27	2.68/2.68
	Alder	87	103	7.4	2.7	121	70	51	26	26	52	0.66/0.49
	Locust	84	100	8.1	3.4	117	60	57	25	18	44	0.76/0.57
	Tree strips	43	59	8.2	3.0	106	52	55	13	−9	4	1.19/0.93
	AGFS	54	70	3.8		153	100	54	11	5	16	0.91/0.77

[a] N input = N_2 Fixation + N in seed + N deposition (ave. 16 kg N ha^{-1} yr^{-1})

[b] Harvested products

[c] Unharvested products (straw of winter wheat and winter rye, green manure of GCA, unharvested biomass of potato, sunflower) and leaf litter of trees

[d] N uptake = N contained in the aboveground crop biomass

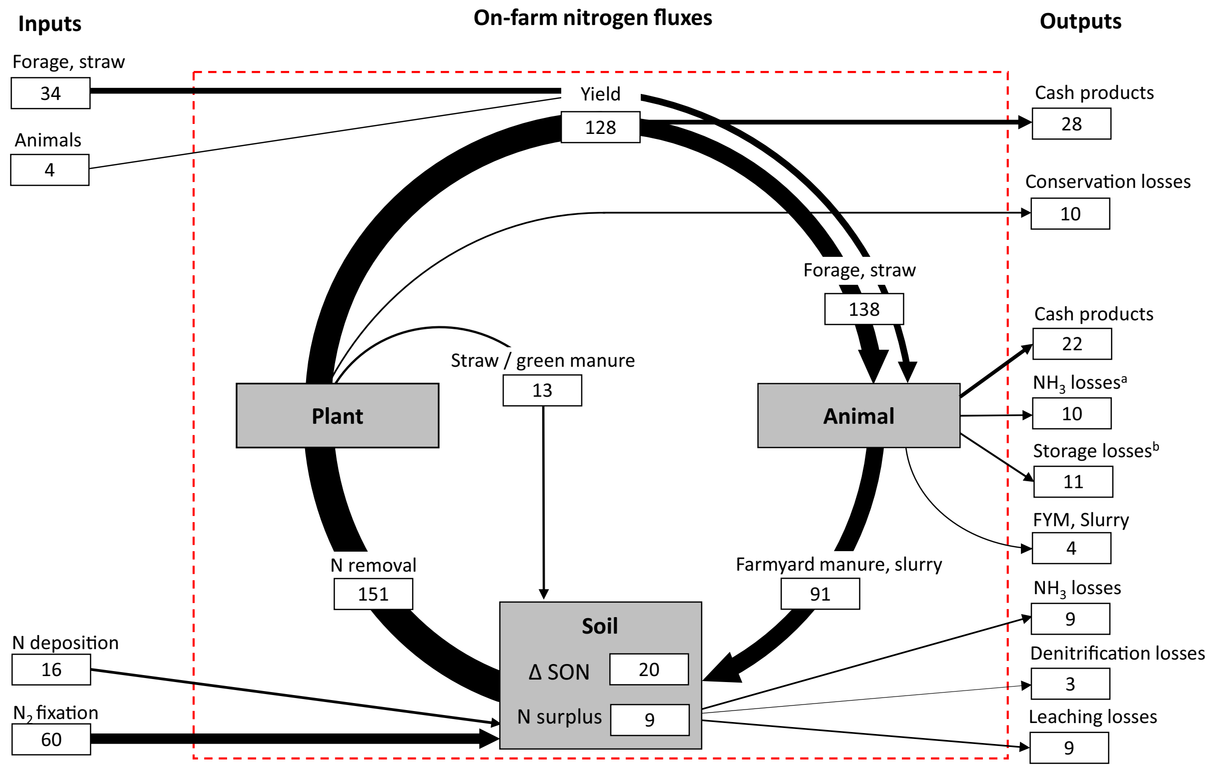

Fig. 2 On-farm nitrogen cycle of the organic mixed farming system (31.1 ha arable land, 18.2 ha permanent grassland), 1999–2002. Adapted from Küstermann et al. (2010). Unit: kg N ha^{-1} yr^{-1}. [a]Losses of ammonia in animal housing systems, [b]N losses during storage of slurry and farmyard manure

and 65 %, respectively. Because the N cycle of the T_{AGFS} area was less intensive compared to the N cycle of the C_{AGFS} area, the establishment of AGFS led to an extensification of the low-N-input organic system.

The intensities of N cycling, the effects on Δ SON, and the N surplus of the C_{AGFS} and T_{AGFS} areas in conventional AGFS were very different (Fig. 5). In the conventional C_{AGFS} area, the N input was mainly from mineral N, and the output was via the harvest of cash crops; both were at a very high level. The input (60 kg N ha^{-1} yr^{-1}) and output (46 kg N ha^{-1} yr^{-1}) of the T_{AGFS} area were much lower (no mineral fertiliser input, low N content in harvested wood). Because 78 % of the N in the conventional C_{AGFS} area was removed by harvesting the crops, only 22 % of the N taken up by plants was returned to the soil. In contrast, 52 % of the total N uptake was returned in the conventional T_{AGFS} area.

Interactions and N fluxes between the subsystems (T_{AGFS} area and C_{AGFS} area) of organic and conventional AGFS were not analysed in this study and are therefore not shown in Figs. 4 and 5.

Discussion

Characteristics and restrictions of the modelling approach

System boundaries and N fluxes

Our N-balance model described agricultural farms as systems which respond to interferences like structural changes and alterations in intensity and technology. All subsystems of a farm (soil–plant–animal–environment) are linked via N fluxes, which enable the interactions between crop production and animal husbandry to be simulated. In order to analyse the effects on the N balance, NUE, and N loss potential brought by the change of farming systems, examining only the relevant N fluxes was sufficient. Our N-balance model is based on the algorithms of the model REPRO, which the N losses can be further specified as N losses via NH_3 emission, denitrification, and leaching (see method description in Küstermann et al. 2010).

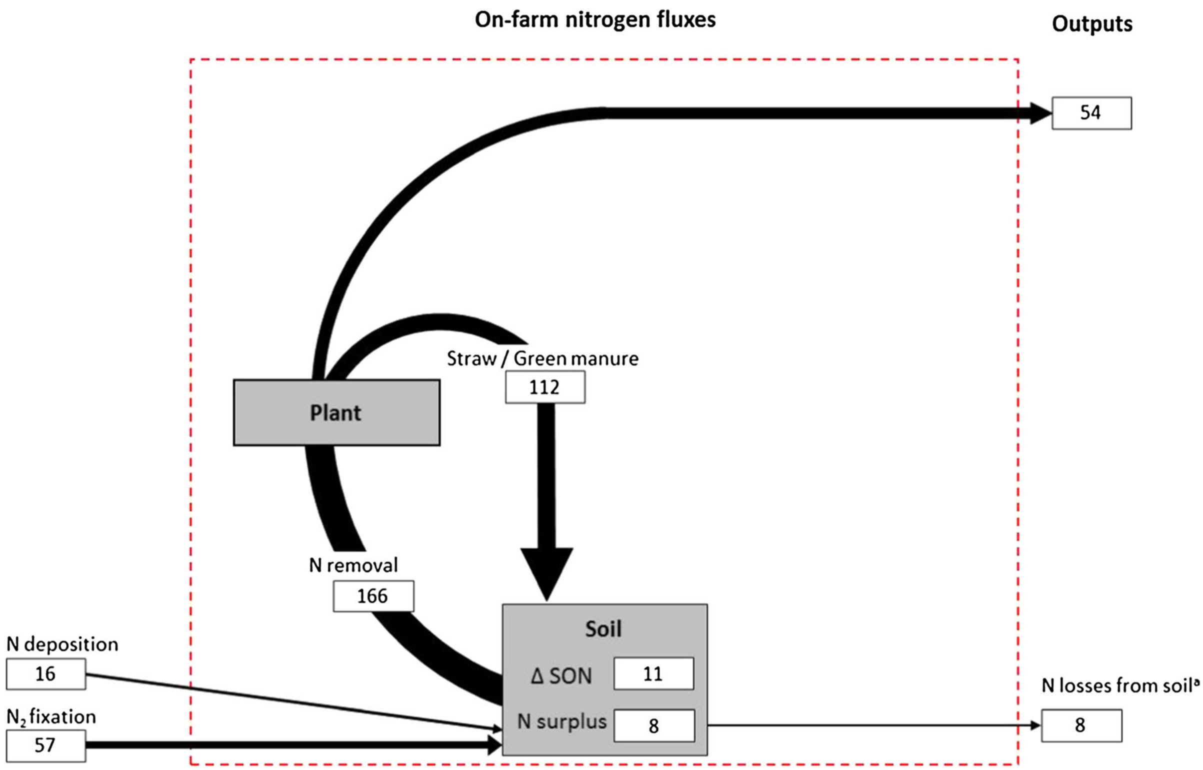

Fig. 3 On-farm nitrogen cycle of the organic arable farm, 31.1 ha arable land, 2009–2012. Unit: kg N ha^{-1} yr^{-1}. [a] N losses from soil = NH_3 losses, denitrification and leaching losses (not specified)

However, these N losses were not analysed in this study.

In agroforestry systems, nitrogen may be transferred between the tree strips and the crop area, in the form of litter or through N taken up by tree roots reaching deeper soil horizons. Hence, the N input, N surplus, and Δ SON may be affected in the interactive zone. Such interactions between the subsystems were not analysed in this study. However, because the results reported in this study were from the first stage of long-term experiments, we can expect that the interactions between the tree and crop subsystems were not yet that significant (Lin et al.).

Symbiotic N_2 fixation

Because symbiotic N_2 fixation was the most important N input for the organic farming and tree subsystems, the accuracy of its determination is decisive for the accuracy of the N balance sheets. However, modelling the symbiotic N_2 fixation of trees based on site-specific conditions is challenging because of various influencing factors (e.g. pH, moisture, temperature and nutrition level of soils) (Danso et al. 1992; Noh et al. 2009). Because the aim of this study is to understand the effects of different farm management on the whole farm system, a certain level of uncertainty in the fluxes is acceptable. The $\%N_{dfa}$ method (description in section "Nitrogen balance and NUE") seems to be appropriate in this context. Nygren et al. (2012) reviewed the $\%N_{dfa}$ of N_2 fixing trees in AGFS from 38 case studies and 19 tree species and concluded a general average of 59 ± 16.6 %, which is influenced by several factors including tree species, sampling season, and pruning frequency.

The calculated symbiotic N_2 fixation of black alder and black locust in this study (88–104 kg N ha^{-1} yr^{-1} and 86–101 kg N ha^{-1} yr^{-1}) was within the range found in literature (alder: 10–266 kg N ha^{-1} yr^{-1} (Bormann et al. 1993; Hurd et al. 2001; Lee and Son 2005; Sanborn et al. 2002; Son et al. 2007; Uliassi and Ruess 2002; Uri et al. 2011); black locust:

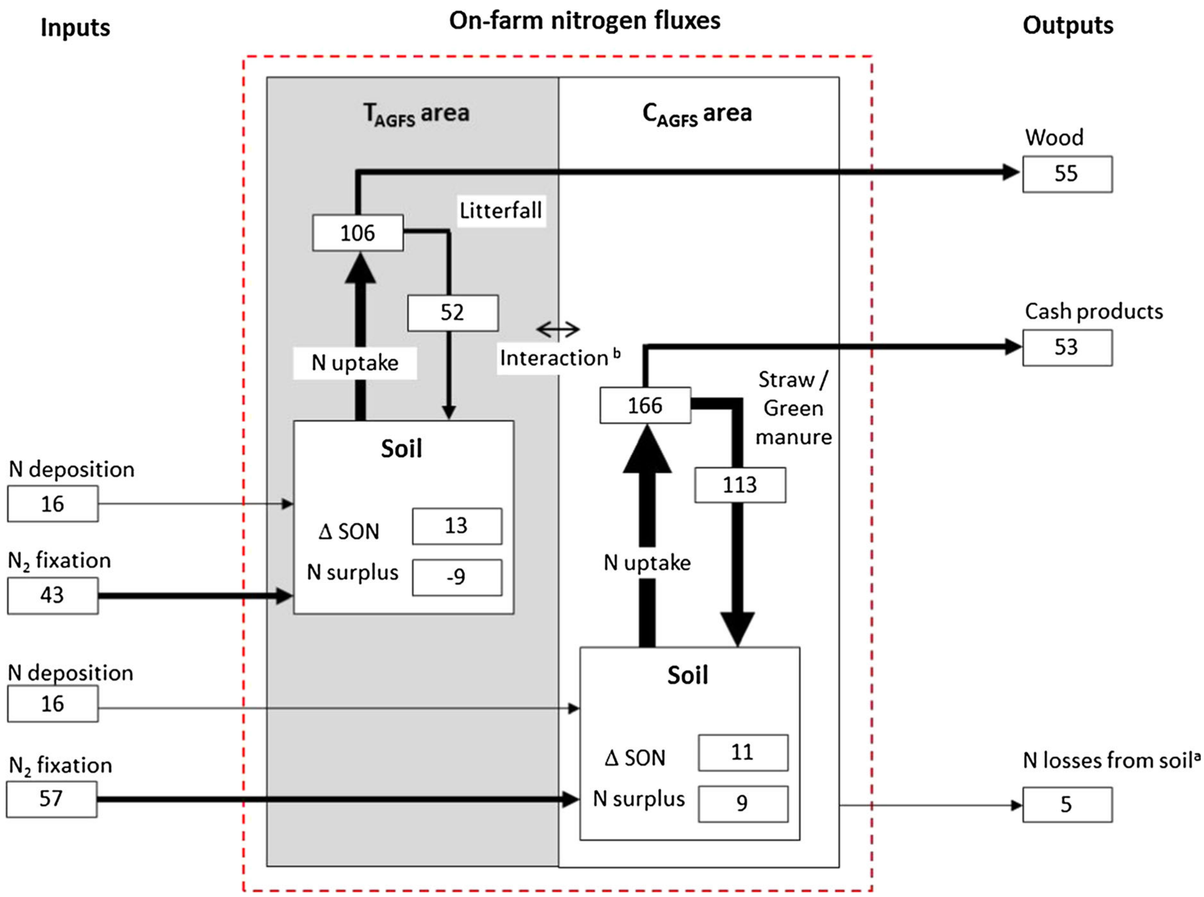

Fig. 4 On-farm nitrogen cycle of the organic agroforestry system, 2009–2012. Unit: kg N ha^{-1} yr^{-1}. [a] N losses from soil = NH_3 losses, denitrification and leaching losses (not specified). [b] Interaction between T_{AGFS} area and C_{AGFS} area (not analysed in this study)

23–112 kg N ha^{-1} yr^{-1} (Boring and Swank 1984; Bormann et al. 1993; Danso et al. 1995; Noh et al. 2009)).

Soil organic nitrogen

Due to the lack of available data, it is commonly assumed that soil N is at steady state (Δ SON = 0 kg N ha^{-1} yr^{-1}) when conducting N balances (Schröder et al. 2003). However, ignoring Δ SON can lead to non-negligible effects (positive or negative) on the N loss potential. In our N balance, Δ SON was calculated based on parameters and algorithms from long-term field experiments with consideration of crop yield, management, soil and climate conditions (Brock et al. 2012a, b; Leithold et al. 2015), but the derivation of Δ SON of trees was based on a comparatively small amount of existing literature. The accumulation or depletion of soil nitrogen by trees is largely influenced by site conditions (e.g. treatment before establishment of trees and soil N content), the soil layer measured, and the year after tree establishment (Jug et al. 1999; Uri et al. 2014). The actual Δ SON of N-fixing trees could be higher or lower than the amount calculated by our approach, and would accordingly change the amount of N surplus.

Nitrogen-use efficiency

Nutrient-use efficiencies can be defined in different ways: crop yield per unit of nutrient applied (partial factor productivity); crop yield increase per unit of nutrient applied (agronomic efficiency); nutrient in harvested crop per unit of nutrient applied (partial nutrient budget); or increase in aboveground crop uptake per unit of nutrient applied (recovery

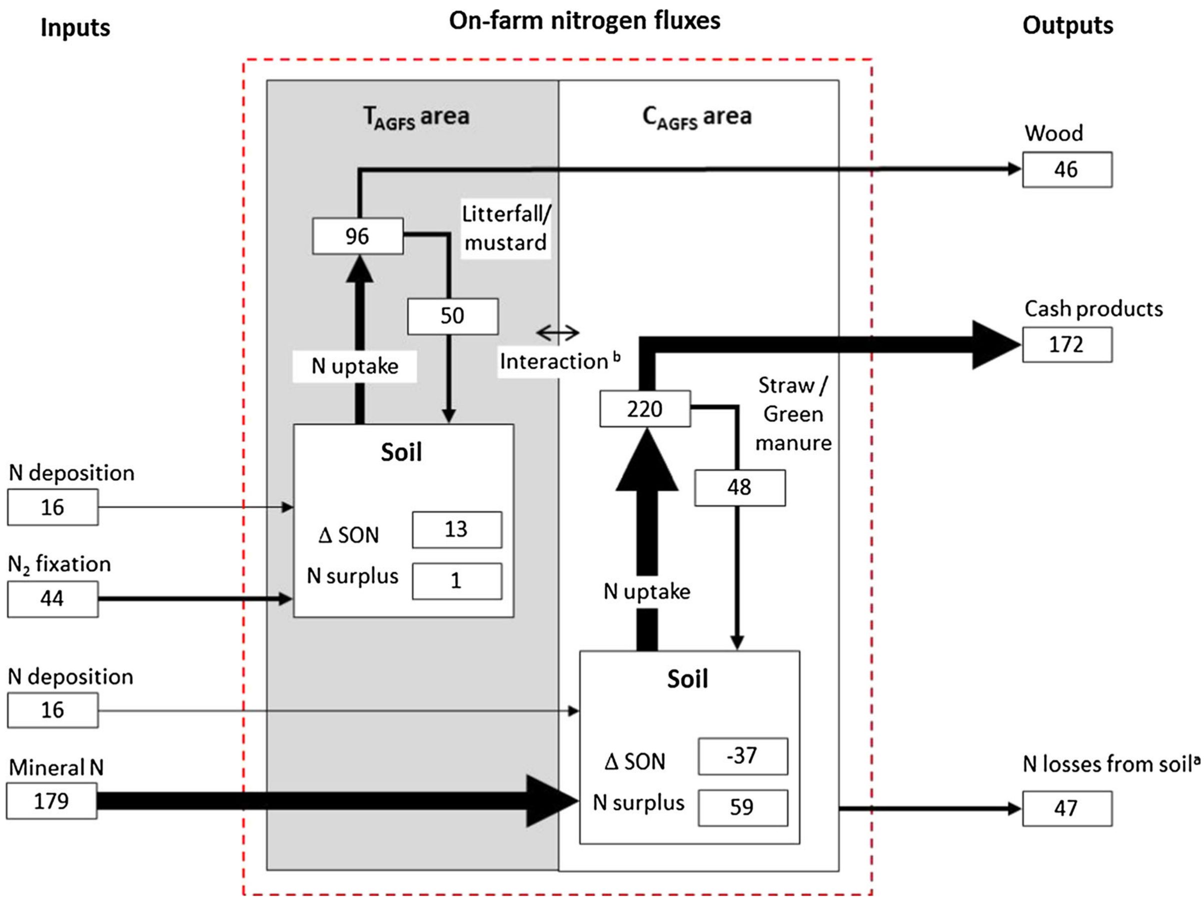

Fig. 5 On-farm nitrogen cycle of the conventional agroforestry system, 2009–2012. Unit: kg N ha^{-1} yr^{-1}. [a] N losses from soil = NH_3 losses, denitrification and leaching losses (not specified). [b] Interaction between T_{AGFS} area and C_{AGFS} area (not analysed in this study)

efficiency). In addition, some NUE calculations only consider nutrient inputs derived from fertilisers, others include nutrients from the mineralization of soil organic matter, crop residues, or manures over several crop cycles (Keating et al. 2010). These different definitions of nutrient-use efficiency have different areas of application in agricultural science and management. We defined NUE as N output in relation to N input because it considers all the relevant inputs and outputs, and reflects not only the relationship between agricultural production and resource consumption (Godinot et al. 2014) but also the management at farm level.

Godinot et al. (2014) proposed a new indicator, system nitrogen efficiency, to improve NUE. They argued NUE has the following disadvantages: (1) Δ SON is not considered, (2) indirect N losses outside the farm are not included, (3) external inputs but not producing them on farm is favoured, and (4) the quality of outputs are not distinguished (e.g. manure is not distinguished from other crop products). Gerber et al. (2014) also suggested the life cycle thinking should be incorporated in the assessment of NUE. The NUE in our study was analysed with the consideration of Δ SON. Because both soil surface balance and farm-gate balance are integrated in our model, the bias that "relying on external input is more efficient than being self-sufficient" is partly solved. The system boundary of this study is within the farm; it is set according to the aim of this study. If today we want to analyse the whole production process of food (or bioenergy), we would expand the system boundary and combine our method with life cycle assessment; N losses outside the farm would also be integrated.

Nitrogen balance of Scheyern Research Farm

N surplus

The N surplus of the conventional farming systems (68, 54, and 47 kg ha^{-1} yr^{-1}, with Δ SON; 44, 21, 21 kg ha^{-1} yr^{-1}, without Δ SON; see Tables 1, 2 , 3) was much lower than the average N surplus in Germany (100 kg N ha^{-1} yr^{-1}, Umweltbundesamt 2014). Our results show that under the conditions of high-N-input farming, a considerable reduction in the N surplus is possible without negative yield effects. The N surplus of the organic farming systems (3, 8 and 5 kg ha^{-1}, with Δ SON; 38, 19, 16 kg ha^{-1} yr^{-1}, without Δ SON; see Tables 4, 5, 6) was within the optimum range (0–50 kg N ha^{-1} yr^{-1}; Christen et al. 2009; Hülsbergen 2003) recommended from an environmental perspective.

Even though the N balance of the whole system was positive and resulted in a positive N surplus, some crops had a negative N balance. The negative N balances of crops can be partly explained by the N uptake of mineralised soil N and/or N from crop residues (N transfer within the crop rotation), but they can also indicate an over- or underestimation of N balance parameters (Δ SON, N deposition, N_2 fixation, etc.).

Figure 6 shows the relation between N input and N surplus of the Scheyern Research Farm, as well as of organic and conventional farms in southern Germany with comparable soil and climatic conditions (Hülsbergen et al. 2012). Even though a lower N input does not guarantee a lower N surplus, a positive correlation is indicated. Most of the organic arable farms were low N-input systems (110–210 kg N ha^{-1} yr^{-1}) with a low N surplus (<0–30 kg N ha^{-1} yr^{-1}). The organic mixed farms had a medium level of N input (160–200 kg N ha^{-1} yr^{-1}) and low N surplus (0–35 kg N ha^{-1} yr^{-1}); the conventional arable farms were high-N-input systems (210–300 kg N ha^{-1} yr^{-1}) with moderate to high N surpluses (45 to >100 kg N ha^{-1} yr^{-1}).

At the Scheyern Research Farm, the conversion of the farm structure and management, i.e. from mixed farming (1999–2002) to arable farming (2009–2012), led to a considerable reduction of N input in the organic farming systems. However, this change did not further decrease the N surplus. In contrast, for the conventional farming systems, the positive effect of the improved management (2009–2012) was clear, and a further reduction of both N input and N surplus was found after the conversion to agroforestry. The transition and optimization resulted in lower N inputs

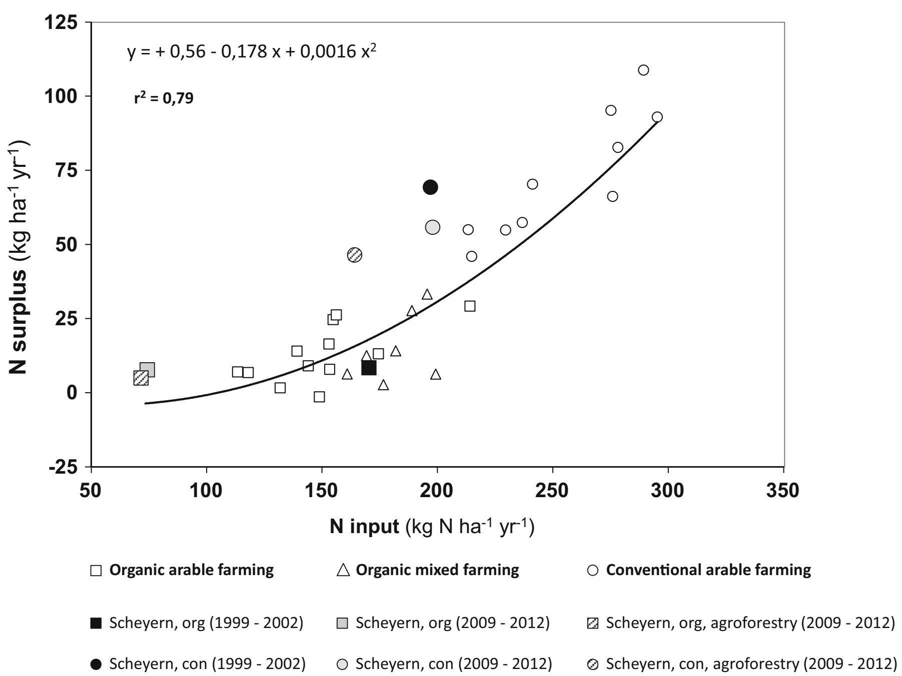

Fig. 6 Correlation between nitrogen input and nitrogen surplus. Data analysed for Scheyern Research Farm and 56 organic and conventional farms in Germany (revised from Hülsbergen et al. 2012)

for the farming systems in Scheyern (2009–2012) compared to other commercial farms. However, the regression function shown in Fig. 6 indicates that the N surplus of farming systems in Scheyern, could, potentially, be reduced further.

The results from the organic AGFS were consistent with the conclusion made by Rosenstock et al. (2014) that the theoretical N surplus of legume-based AGFS with low N input should be around 0 kg N ha^{-1} yr^{-1}. However, this also depends on the N mineralization potential (soil fertility) and the N deposition. In both conventional and organic agroforestry systems, poplar and willow had negative N surpluses while black alder and black locust had medium (positive) N surpluses. The negative N surplus of poplar and willow was due to the uptake of N, although no N was applied to the tree strips. This N may be N remaining in the system from previous land use (mineral N and N in crop residues from previous arable farming) or was transferred from the C_{AGFS} area. It is also possible that this N was from SON and therefore indicates the depletion of SON. Further research will be conducted in the future to analyse these N fluxes, interactions, and to measure the Δ SON of our experiments.

Nitrogen-use efficiency

Tilman et al. (2002) warned of a globally decreasing trend of cereal yield obtained per unit of N fertiliser applied since 1960, which implies a reduction of the nitrogen-use efficiency. They reported that only 30–50 % of the applied N fertiliser is taken up by crops. The highest N fertiliser efficiency is achieved with the first increments of N fertiliser, and declines with further additional N.

In this study, the NUE of crop areas of organic farming systems (0.87–0.98, with Δ SON) was higher than that of conventional farming systems (0.69–0.76). Torstensson et al. (2006) reported the NUE of organic arable fields in southern Sweden, which ranged from 0.34 (arable farming system) to 0.91 (mixed farming system). The NUE of conventional systems ranged from 0.71 to 0.74, with a higher NUE found in the system with cover crops. Spiertz (2010) estimated the NUE of high-N-input systems (150–300 kg N ha^{-1}) and low-N-input systems (100–150 kg N ha^{-1}) and found values between 0.30–0.60 and 0.40–0.70, respectively. Li et al. (2007) showed that the NUE of conventional farming systems in the North China Plain increased from 0.18 to 0.75 with a decrease in N fertiliser. These examples illustrate the high variability of the NUE of organic and conventional farming systems depending on site and management conditions. The high NUE presented in this study may be the result of ideal soil–climatic conditions, and thus high yield potential, of optimised N-management and technologies, and of the high-yielding varieties used at the Scheyern Research Farm. However, a high NUE does not necessarily indicate that the N surplus does not exceed critical environmental thresholds. The amount of mineral N remaining after the harvest plays an even more important role in the environmental N pollution issue (Spiertz 2010).

Soil organic nitrogen

We found an accumulation of SON in organic farming systems but a depletion of SON in conventional farming systems. The modelled results were confirmed by the SON contents measured at defined measuring points (Küstermann et al. 2008). The latest soil inventory conducted at Scheyern Research Farm, based on measured SON contents, revealed an increase in SON of 44 kg ha^{-1} yr^{-1} in organic mixed farming and a decrease of 38 kg ha^{-1} yr^{-1} in conventional arable farming since 1991 (Küstermann et al. 2010). The SON accumulation of the organic arable farming system was the result of the crop rotation (with legumes), straw and green manure.

Jug et al. (1999) found that the soil N in the top 30 cm in short rotation forestry in Germany could be both positive and negative (range from −50 to 20 kg N ha^{-1} yr^{-1}) 8–10 years after establishment. Uri et al. (2014) reported the N in the top 10 cm soil of grey alder in Estonia increased by 26.4 kg N ha^{-1} yr^{-1} after 14 years of cultivation. This study was conducted based on data collected in the first 4 years after the establishment of AGFS and the change in SON may not yet be detectable. The literature suggests that a SON accumulation is detectable, at the earliest, 5–10 years after the change in farm management (Hülsbergen 2003; Körschens 1992). Due to the difficulty in assuming a correct value of SON for poplar and willow and due to the short duration of the experiment, we used the assumption of Petzold et al. 2010 and calculated the N balance with a SON of 0 kg N ha^{-1} yr^{-1}. Less literature exists for locust and alder and the assumption of an SON accumulation of

30 % of the fixed N seemed to be appropriate, also with regard to the comparison of N-fixing and non-N-fixing tree species.

Opportunities to improve the use of nitrogen in farming systems

One of the central questions of this study is: can we increase the DM yield, optimise the NUE, sustain soil fertility, and reduce N surplus at the same time? Our results showed that (1) with better crop varieties and optimised farm management, the DM yield and NUE can be increased with a simultaneous reduction in N surplus and the related negative environmental effects, and (2) establishing conventional AGFS has positive effects on the increase of NUE, the accumulation of SON, and the reduction of N surplus.

The results of this study also showed that the crop area of the organic mixed farming system had the highest DM yield, NUE, Δ SON, and the lowest N surplus among the three organic farming systems. The good results from the organic mixed farming system were attributed to the intensive internal N cycle between soil–plant–animal, compared to the soil–plant cycle of organic arable farming. In organic mixed farming systems, animal manure and slurry can also be applied flexibly in both space and time, according to expected plant needs.

Bryzinski and Hülsbergen (2015) detected significantly higher DM yields in fields applying FYM and slurry (organic mixed farming systems) compared to fields applying straw and green manure (organic arable farming systems) in a long-term field experiment in southern Germany. Schmid et al. (2013) also found that crop areas in organic mixed farming systems performed better than organic arable farming systems regarding DM yield, energy recovery, nitrogen use efficiency, SON accumulation, and N surplus, in 28 farms in Germany. The effects from establishing organic mixed farming systems (compared to those from arable farming systems) shown in these studies confirm the results of this study.

However, even though there were clear differences in DM yield and N output between the crop rotation of the organic mixed farming system (DM yield: 6.9 kg DM ha^{-1} yr^{-1}; N output: 140 kg N ha^{-1} yr^{-1}) and the organic arable farming system (DM yield: 2.5 kg DM ha^{-1} yr^{-1}; N output: 54 kg N ha^{-1} yr^{-1}) in this study, the N output of their cash crops were comparable (organic mixed farming system: 50 kg N ha^{-1} yr^{-1}; organic arable farming system: 54 kg N ha^{-1} yr^{-1}, see Figs. 2, 3). This reduction in cash crop-N in the mixed farming system was expected because of the conversion loss of N from plant protein to animal protein (Oenema and Tamminga 2005). Other N loss sources in an animal subsystem are, for example, the emission of ammonia in animal housing systems and during storage of slurry (Leip et al. 2011). The NUE of mixed farming systems is therefore lower than NUE of arable farming systems, when the N balance is calculated at farm scale (Leip et al. 2011).

The negative N balance of non-N_2 fixing trees (poplar and willow) indicated a low N loss potential. However, it also indicated that there is no potential for SON accumulation. The N uptake of poplar was also rather high. Therefore, in the long run, an additional N input for poplar and willow could be necessary. Their negative N balance offers the chance to reduce the N surplus and N loss potential of the whole AGFS system. In contrast, the N_2 fixing trees (black alder and black locust) lead to positive N balances. The SON accumulated by them offers the chance for N transfer and to improve soil fertility in the interaction zone between the T_{AGFS} and the C_{AGFS} areas in an agroforestry system.

Conclusion

Case studies on farms, like the Scheyern Research Farm, represent a valuable and necessary supplement to field experiments. A decisive advantage is the complete and realistic description of farm internal mass fluxes in the soil–plant–animal–environment system.

N balancing tools have become widely used by scientists, policymakers, consultants, and farmers as useful instruments for planning and control of on-farm nitrogen management. This study improved an existed N balancing method by integrating the N parameters for crop rotation and tree strips, so the improved method can be used in mixed farming, arable farming, and agroforestry systems. Simple N balance approaches neglect internal pools and flows of nitrogen on farms. However, if special emphasis is to be given to system analysis and optimization, farm internal structures and processes have to become the focus of attention. An analysis of nitrogen flux relationships facilitates the comprehensive understanding of a system. Our approach reveals the causes of NUE differences and is the precondition for scenario calculations aimed at reducing N losses.

The results in conventional and organic agroforestry showed that poplar and willow are especially suitable for high-N-input systems (conventional farming) because the negative N surplus balances the high surplus of those systems; black alder and black locust are, in contrast, ideal for low-N-input-systems (organic farming) because of their ability to accumulate SON and offer additional N sources. The improved conventional arable farming and conventional agroforestry system in this study showed that a significant reduction of N surplus without negative yield effects is possible. Mixed farming systems are one of the best ways to run organic farming systems sustainably regarding the use of N, and organic AGFS has the potential to increase the DM yield of the whole system, to improve nitrogen-use efficiency, and to reduce negative environmental effects. Our findings can be used in setting up the strategies and policies for agricultural N surplus reduction (e.g. encouraging the establishment of different agroforestry systems for organic and conventional farms), therefore mitigate the environmental problems brought by agricultural N emissions.

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