ORIGINAL ARTICLE

Nitrogen-use efficiency of organic and conventional arable and dairy farming systems in Germany

Lucie Chmelíková · Harald Schmid · Sandra Anke · Kurt-Jürgen Hülsbergen

Abstract Optimising nitrogen (N) management improves soil fertility and reduces negative environmental impacts. Mineral N fertilizers are of key importance in intensive conventional farming (CF). In contrast, organic farming (OF) is highly dependent on closed nutrient cycles, biological N fixation and crop rotations. However, both systems need to minimise N balances and maximise nitrogen-use efficiency (NUE). NUE of organic and conventional crop production systems was evaluated in three regions in Germany by analysing N input, N output and N balance of 30 pairs of one OF and one CF farm each from the network of pilot farms for the period 2009–2011; indicators were calculated using the farm management system REPRO. CF had higher N input in all farm pairs. In 90% of the comparisons, N output of CF was higher than OF, in 7% it was the same and in 3% lower. NUE was higher in 60% of the OF, the same in 37% and lower in only 3%. The NUE of crop production in OF was 91% (arable farms: 83%;

mixed/dairy farms: 95%) and the NUE in CF was 79% (arable farms: 77%; dairy farms: 80%). N balance was lower in 90% of the OF. The yearly average N balance was four times higher in CF (59 kg N ha^{-1} a^{-1}) than in OF (15 kg N ha^{-1} a^{-1}). The results show a huge individual variability within OF and CF. Organic mixed/dairy farms had the lowest N balances and the highest NUE. A further expansion of OF area can help to reduce high N balances and increase the NUE of crop production.

Introduction

In Western Europe, high nitrogen (N) balances have been reported in agriculture for decades, leading to N losses in the form of ammonia, nitrous oxide emissions and nitrate losses to groundwater, which can have negative environmental effects and contribute to climate change (Blanke et al. 2018; Bleken et al. 2005; van Grinsven et al. 2012). In Germany, the N balances of the last 10 years have, almost continuously, been between 80 and 100 kg ha^{-1} a^{-1} (BMEL 2020).

The causes are complex (Wiesler et al. 2016). Despite technical innovations such as improved liquid manure application technology, the use of stabilized N

L. Chmelíková (✉) · H. Schmid ·
S. Anke · K.-J. Hülsbergen
Chair of Organic Farming and Agronomy, TUM School of Life Sciences, Technical University of Munich, Liesel-Beckmann-Str. 2, 85354 Freising, Germany
e-mail: lucie.chmelikova@mytum.de

fertilizers (Petersen et al. 2013), and sensor-supported, site-specific fertilization (Prey and Schmidhalter 2019), N balances have not decreased significantly. This is due to the further expansion, intensification and regional concentration of livestock farming with high levels of slurry usage. Further, high N balances are also found on intensive conventional arable farms (Biernat et al. 2020). In this context, the question arises whether the expansion of OF required by the German Sustainable Development Strategy (German Federal Government 2016) can contribute to a significant reduction in N balances and to the solution of environmental problems. The development of N balances depends not only on the OF area (currently 1.5 million ha in Germany, an increase of 50% in the last 5 years), but also on the way in which OF is carried out. A majority of studies show that less N is used in OF due to OF regulations (no mineral N, limited animal stock), but this does not always mean low N balances (because the yields are also lower) or high NUE (Chmelíková and Hülsbergen 2019). Only a few studies have analysed how the structure of organic farms (e.g. arable farms and dairy farms) and the fertilization intensity (N input) influence the N balance and nitrogen-use efficiency (NUE). This differentiation is urgently needed in order to be able to correctly assess the potential for N reduction in OF.

Intensive animal husbandry and its spatial concentration, often in combination with biogas plants (Finzi et al. 2020; Theobald et al. 2015), increases the risk of N emissions with negative environmental impacts on groundwater (nitrate), climate and eutrophication (nitrous oxide, ammonia), and biodiversity. The global limits of N input have been greatly exceeded (Rockström et al. 2017). A significant reduction in N input and the efficient use of N in agriculture are necessary. Therefore, researching NUE is an urgent priority. Most studies on N balances are based on field experiments (Alaru et al. 2014; Aronsson et al. 2007; Clark et al. 1998; Mayer et al. 2015; Swain et al. 2014; Torstensson et al. 2006), not on real farms. The design of field experiments does not always represent the conditions of real farming systems, their structure (crop rotation), management (fertilization) and yield level. According to Dal Ferro et al. (2017), monitoring studies of real organic and conventional farms, taking into account all production practices, are required. Attention should be paid to the study scale (field, farm, region) because it affects results such as yield gap

calculations (Ponti et al. 2012). Moreover, Gomiero et al. (2011) noted the issues with comparative analysis, e.g. different geographical, climatic and soil conditions, different crops, different crop rotations and different types of inputs. Data from real farms are often heterogeneous and not easily comparable. There are considerable differences depending on location, soil and climate conditions. The comparison of organic and conventional farming systems is often insufficient and gives conflicting results due to the considerable variability in organic and conventional systems, e.g. farm structure and management (Sanders and Heß 2019). Meta-analysis is considered more robust than standard approaches to quantitative literature reviews, because it is able to summarize heterogeneous data derived from different methods (Hunter and Schmidt 2007; Koricheva et al. 2013). However, even in meta-analyses, there are enormous methodological problems (incomplete data, fertilization systems and crop rotations that do not represent how farmers actually manage their farms), as shown by the evaluation of field experimental data on N efficiency (Chmelíková and Hülsbergen 2019). Thus, the appropriate comparison of organic and conventional systems is very difficult.

There are fundamental differences between organic and conventional farming in terms of N input into agricultural soils. In OF, N contribution from biological N_2 fixation due to the symbiosis between legumes and rhizobia can provide substantial amounts of N to plants and soil, and can reduce the need for N fertilizers (Herridge et al. 2008). Further, organic systems additionally obtain N from animal or green manures. In Regulation (EEC) No. 2092/91, livestock stocking rates are capped, hence preventing losses to the environment. This lower input results in lower yields (output). On the other hand, CF has higher N inputs via mineral fertilizers and intensive animal husbandry often using additional external feedstock. This higher input can result in higher N balances and N losses. In general, a higher N balance increases the risk of environmentally-relevant N losses in the form of nitrate, ammonia and nitrous oxide (Clark and Tilman 2017; Erisman et al. 2011; Galloway et al. 2008). More effective regulation of N emissions has been achieved in other sectors (e.g. transport) than in agriculture (Fowler et al. 2013). Further, management practices differ in their effectiveness towards improving NUE (Gardner and Drinkwater 2009).

Due to the officially limited N inputs from livestock-based land use, diverse legume-based crop rotations with catch crops and permanent land cover are possible strategies for improving NUE. For example, dairy/mixed farms with a diverse structure and efficient N recycling through internal and external nutrient/material cycles, can achieve high NUE (Küstermann et al. 2010). On the other hand, there are not inconsiderable risks for N losses even under OF conditions, e.g. nitrous oxide after ploughing of clover-grass or green manure (Heuwinkel et al. 2005; Reinsch et al. 2018). Further, N from the organic fertilizers used in OF (e.g. compost) is, due to its organic bonding, initially stored in the soil N pool and can be used by the plants in the long term, often even after decades (Hartl and Erhart 2005). However, there is uncertainty regarding whether OF can achieve higher N efficiency under comparable site conditions. There are also substantial N losses in organic farming, e.g. in crop rotations after clover to winter wheat (Pandey et al. 2018). Site- and weather-dependent N mineralization from the soil does not always coincide with plant requirements and organic fertilizers have a relatively high loss potential, e.g. via ammonia. Due to the diversity of OF and CF, the complexity of the N cycle and the sometimes contradictory statements in the literature, it is not clear whether lower N balances are due to lower N inputs or if the NUE is also different. In the United States, maize yield stabilized and NUE decreased at N fertilizer input levels above 150 kg N ha^{-1} yr^{-1} (Lu et al. 2019). According to Beukes et al. (2020), there is no single optimum point for N fertilizer input, there is more likely a zone where N output is relatively high (not maximal) with low N losses. Further, according to Hansen et al. (2017), since 1990 N output has been nearly constant in Danish agriculture with declining N inputs and N balance, probably because of better N utilization of manure and higher livestock production. In 12 European countries, large surpluses occurred in regions with high livestock density, but they were affected by management practices as well (Svanbäck et al. 2019). The influence of different farming types (arable farming, dairy farming) and N intensities on N balance and NUE has not been sufficiently investigated. Häußermann et al. (2020) have shown that the highest N balance and lowest NUE occurred in regions with high livestock density and that regions dominated by arable farming had medium to low N balances.

Nevertheless, the data were provided by the Federal Statistical Office (www.destatis.de) for German regions without taking OF and CF into account.

There are already many studies on the N efficiency of organic and conventional farming systems. Nevertheless, studies often do not consider the whole system and the different conditions for each system. Location- and farm-specific measurements are, however, necessary to increase NUE and to reduce/avoid N surpluses. The Network of Pilot Farms (www.pilotbetriebe.de) was therefore established in Germany in 2009 to enable comparison of farming systems, analysing the whole farm. The present study is unique in that not just individual crops but the whole crop production system is analyzed, with crop rotations and the proportion of grassland specific to each location and typical for each system (organic and conventional, arable and dairy farming systems). Data from farms was sampled in three regions (south, west and north). The east region was not taken into account because of the large differences in farm characteristics, structure and farm size, in comparison to the other three regions. In each region, there were 10 pairs consisting of adjacent organic and conventional farms. In the current study, data from this network and an ongoing project[1] were used. The very comprehensive, detailed data set on farming systems was used to evaluate the N flows in organic and conventional farming. The aim of this paper is to compare N soil surface balances in OF and CF, referring to system-related differences between arable and dairy farming (mixed farming with dairy farming) with typical characteristics and N inputs for each system. Both farming systems are represented by two farming types—arable and dairy farming. The present study estimates the soil surface N balance on farms in Germany and is aimed at comparing the systems and farming types in terms of (a) N input, (b) N output, (c) N-use efficiency (NUE), (d) accumulation or depletion of soil organic nitrogen (Δ SON), and (e) N balance.

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[1] Project "Increasing Resource Efficiency by Optimizing Crop and Milk Production on Whole Farm Level under Consideration of Animal Welfare Quality Aspects".
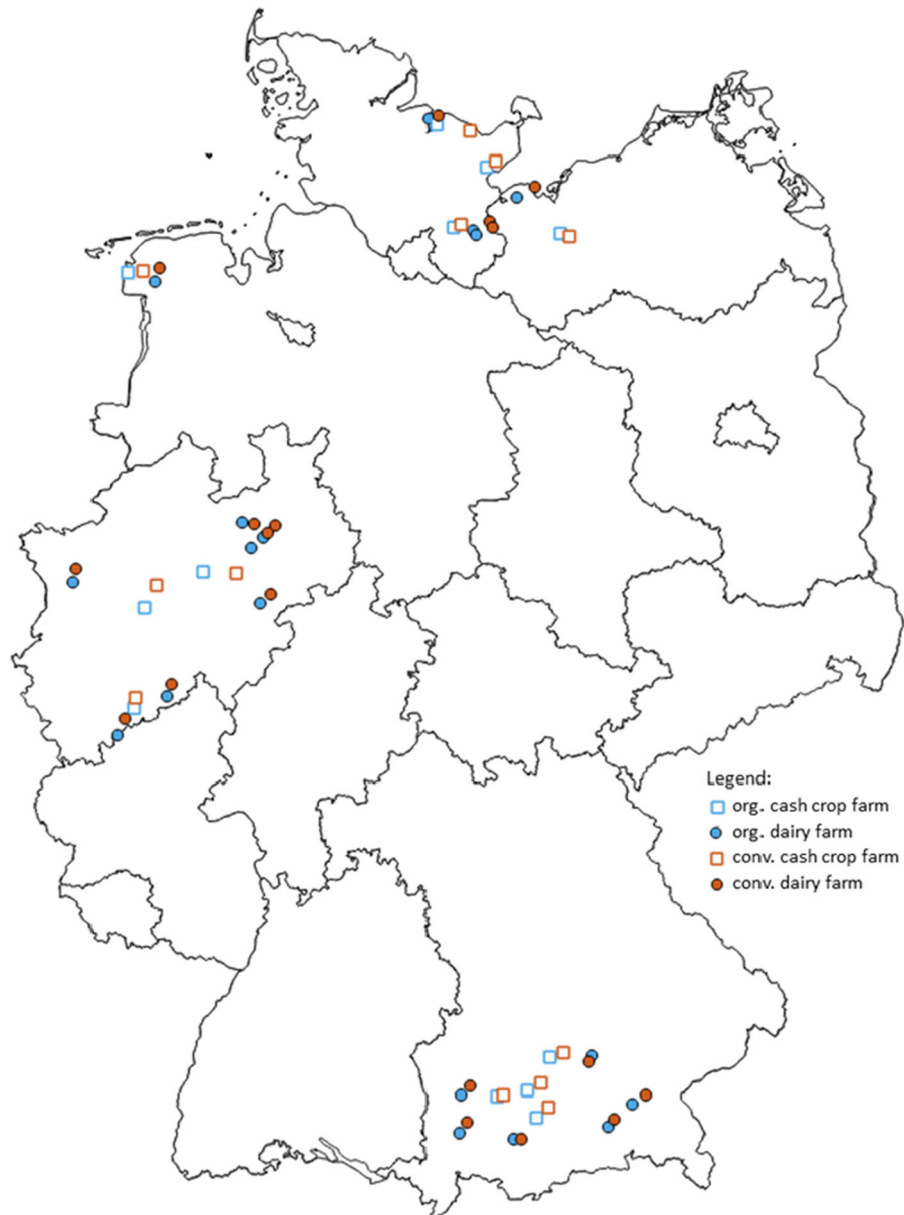
Fig. 1 Location of 30 farm pairs (one organic and one conventional farm) in Germany analysed in this study. In total 60 farms, 18 dairy farm pairs and 12 arable farm pairs

Materials and methods

Study area

Data were collected from 30 organic and 30 conventional farms from the network of Pilot Farms (Fig. 1) in three German regions (south, west and north), starting in 2009. The data came from the project

"Ecological Sustainability of Agricultural Systems—Analyses in a Network of Pilot Farms". The project analysed the environmental sustainability and resource-use efficiency of the farming systems. One focus of the project was the analysis of energy and N balances. In this study, the focus is on the N balance (soil surface balance) in crop production for the period 2009–2011. The network consists of pairs of farms,

Table 1 Characteristics of the project farms

Parameter	Unit	Organic farming system		Conventional farming system	
		Arable farm	Dairy farm	Arable farm	Dairy farm
Number of farms		12	18	12	18
Elevation	m a.s.l	204 (0–588)	260 (3–780)	213 (0–588)	257 (1–780)
Precipitation	mm a^{-1}	771 (591–1109)	863 (536–1507)	771 (591–1109)	863 (536–1507)
Average temperature	°C	8.5 (7.5–9.7)	8.5 (6.9–10.8)	8.5 (7.5–9.7)	8.5 (6.9–10.8)
Soil quality[a]		56 (41–75)	43 (23–64)	58 (40–78)	47 (25–68)
Area	ha	195 (57–511)	183 (30–1317)	261 (65–1224)	104 (30–312)
Cropland	%	94 (73–100)	54 (0–96)	97 (81–100)	60 (0–85)
Cereals	% crop land	57 (36–76)	41 (0–68)	64 (44–95)	40 (0–69)
Grain legumes	% crop land	11 (0–17)	4 (0–16)	0	1 (0–8)
Root crops	% crop land	8 (0–32)	8 (0–24)	14 (0–47)	34 (11–70)
Grass-clover	% crop land	19 (6–33)	40 (17–81)	3 (0–17)	11 (0–46)
Undersowing	% crop land	8 (0–24)	9 (0–28)	0	3 (0–59)
Catch crops	% crop land	18 (0–38)	12 (0–31)	11 (0–42)	13 (0–59)
Crop diversity[b]		2.36 (1.78–3.04)	2.05 (1.01–2.95)	1.62 (0.91–2.41)	1.54 (0.84–2.04)
Livestock[c]	LU ha^{-1} a^{-1}	0.01 (0–0.08)	0.87 (0.27–1.56)	0	1.46 (0.54–2.72)

Units in parentheses represent minimum and maximum values, respectively

[a]Müncheberger Soil Quality Rating (0–100 points) for assessing the agricultural yield potential of German soils (Mueller et al. 2007)

[b]Crop diversity is calculated as the proportion of the individual crop of the total cropped area

[c]Livestock units (LU) are a standardized measure for comparing livestock density with 1 LU being equal to a cow weighting about 500 kg

which are located near each other in the same pedoclimatic area. Organic farms had to be under organic management for at least 7 years. In each region, two farm types (arable farm (AF) and dairy farm (DF)) were present. Farm elevation in the southern region of the Alpine Foreland ranged from 444 to 776 m, in the western region with a maritime climate from 21 to 421 m, and in the northern coastal region from − 4 to 52 m. Farms with differing site and climate conditions were chosen to represent a wide range of management conditions.

Besides regional aspects, selection criteria for the pilot farms were that the farmer worked on the farm full-time, had comprehensive and precise data documentation (field records, livestock husbandry data), made data available and was willing to cooperate. Farm size had to be equal to or larger than the average size of farms in the region. In this study, 12 organic and 12 conventional farms were arable farms, 18 organic and 18 conventional farms were mixed dairy farms, combining dairy and arable farming. There

were only small differences between organic and conventional farms regarding other characteristics such as farm size or soil quality (Table 1). In order to ensure comparability of the farming systems, pig farming, intensive vegetable production and poultry farming were excluded.

System modelling

N fluxes were calculated for the crop subsystem (soil surface balance) for the period 2009–2011. For more details on the soil surface balance, see Fig. 2. The soil surface balance was chosen to ensure comparability of the farms (the same N inputs, N outputs, and system boundary). Equivalent input and output parameters enable the comparable analysis of N balance and NUE.

In dairy farming, the N fluxes of the livestock holdings were investigated to calculate the amount and N content of organic fertilizers (liquid manure, manure), which represent an input in crop production.
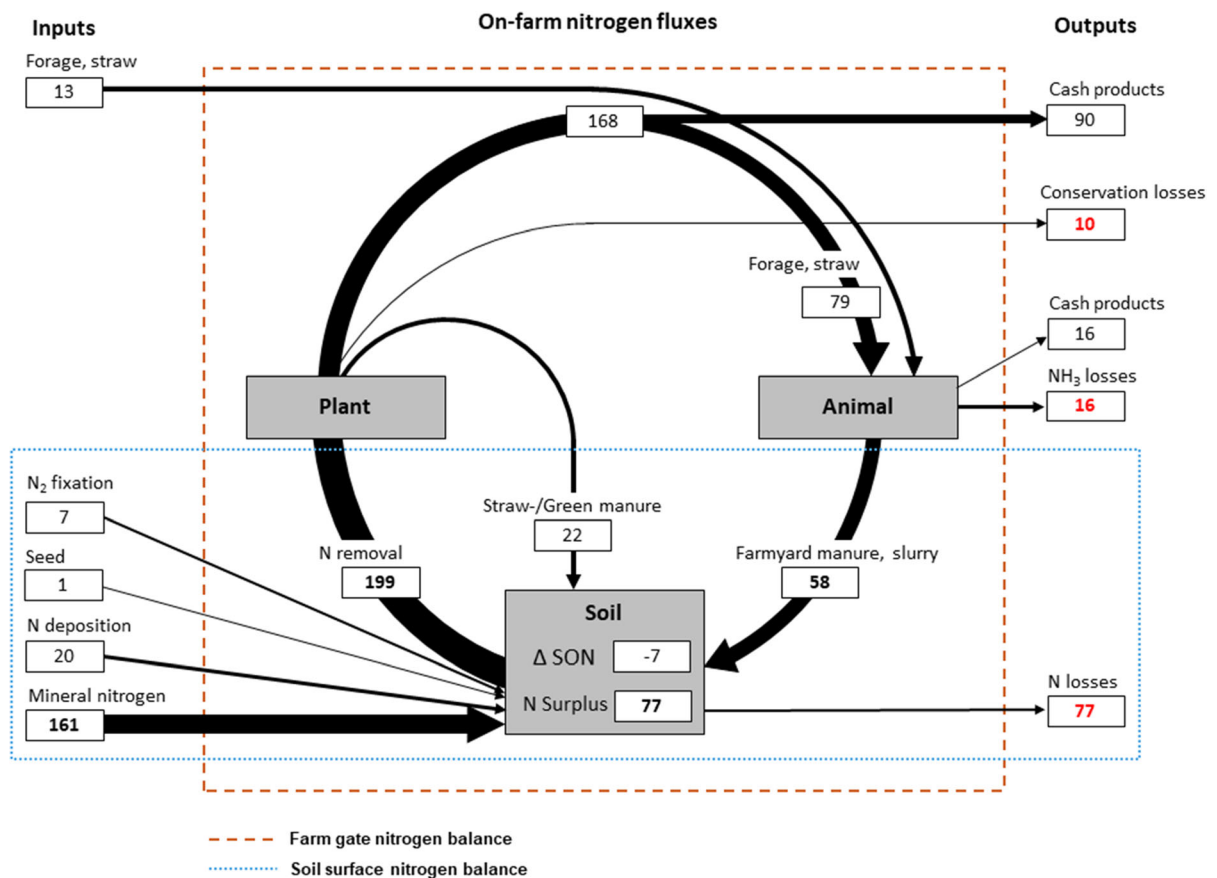
Fig. 2 Examples of N cycles of an organic dairy farm from the network of Pilot Farms. The blue dotted box represents the N balance of the crop production system. N losses from soil are ammonia volatilization, denitrification and leaching losses (not specified). Changes in the stocks of feed and organic fertilizers (liquid manure, manure) are not shown. All values are in kg N ha^{-1} a^{-1}

Other N inputs and outputs of animal husbandry (purchase of feed, animal products sold) are not relevant in the N balance of crop production.

Data about the production process on each pilot farm was taken from field records, supplemented by detailed yearly interviews. Relevant production and management process data (tillage, fertilization, crop protection, etc.) for all fields and all crops were collected yearly on all farms. Crop production data (fertilization, crop rotation, yield etc.) were recorded for each crop type and each field. Complete production processes were recorded—from the first cultivation to harvest, including activities such as fertilizer application. Data on livestock performance and the feeding and housing systems were collected on dairy farms. These data were used for the modelling of N fluxes with the model REPRO (REPROduction of soil fertility, Hülsbergen (2003)). REPRO has integrated methods for calculating N fluxes and N pools based on available farm data, for example symbiotic N_2 fixation, N fluxes in livestock keeping and turnover in soil. It evaluates all relevant N flows in the system soil—plant—animal—environment (Fig. 2). The modelling approach used in this study is described in detail in Küstermann et al. (2010). For further details about system modelling, see the supplementary online material.

N input, N output, NUE and N balance of farm crop production were selected as parameters for both the arable and the dairy farming systems, to ensure comparability of the systems. The N input included N fluxes from symbiotic N_2 fixation, N mineral fertilizers, N organic fertilizers, and N atmospheric deposition. N output considered only the N contained

Table 2 Soil surface nitrogen (N) balance—N input, N output, N-use efficiency (NUE) and N balance of 30 organic (OF) and 30 conventional farming (CF) crop production systems in Germany

	N input (kg N ha^{-1} a^{-1})		N output (kg N ha^{-1} a^{-1})		NUE without Δ SON[a] (%)		NUE with Δ SON (%)		N balance without Δ SON (kg N ha^{-1} a^{-1})		N balance with Δ SON (kg N ha^{-1} a^{-1})	
	OF	CF	OF	CF	OF	CF	OF	CF	OF	CF	OF	CF
Mean	161	266	146	208	91	79	96	76	15	59	6	67
Median	158	265	137	201	90	75	96	73	14	75	5	73
Min	97	177	94	155	61	61	64	59	− 41	− 37	− 41	− 37
Max	240	344	236	310	121	114	121	114	72	124	62	129

[a]Accumulation or depletion of soil organic N

in the harvested plant products. NUE was defined as N output in relation to N input (Halberg et al. 1995). The difference between N inputs and N outputs is defined as the N balance (Halberg et al. 2005).

Data analysis

The percentage differences in N input, N output and NUE of organic and conventional farming systems were evaluated. A difference was defined as relevant if the organic and conventional values differed by ± 10%. Loess smoothing was used to evaluate the relationships between N input and N output, N input and N balance (with/without Δ SON), N input and NUE (with/without Δ SON), N output and NUE (with/without Δ SON). Boxplots for these percentage differences and the relationships were created using R 3.3.3 (R Core Team 2017).

One-way ANOVA was used to evaluate the effects of farming systems and farming types. After obtaining significant results, multiple comparisons using Tukey's HSD test were applied to identify significant differences among the four different variants (OF-AF; OF-DF; CF-AF; CF-DF). The analyses was conducted with all the values of total N input, N$_2$ fixation, organic fertilizer N input, mineral fertilizer N input, N output, NUE and N balance for the farming systems. The analysis was performed using STATISTICA 12 software.

Results

Our results show great variability in farm management (Table 1). A wide range of farms was included, e.g. the livestock maximum on CF was 2.72 LU ha^{-1} a^{-1} and

in OF the maximum was 1.56 LU ha^{-1} a^{-1} (livestock units (LU) are a standardized measure for comparing livestock density with one LU being equal to a cow weighting about 500 kg). In OF, the proportion of grass-clover (DF: 40%, AF: 19%) differed greatly among the farms as well. In CF, there were even some farms without any grass-clover. In CF, mainly maize for fodder production and root crops made up a large proportion of the crop rotation. In the crop rotations of conventional DF, maize and winter wheat were dominant. On the other hand, in organic DF cultivated grass-clover and winter wheat were predominant. For more details on differences in the forage crops of the pilot farms please see Frank et al. (2019). Hence, there were differences in crop diversity and composition of mixtures undersown in cereals (e.g. species rich grass-clover) causing for example differences in ground cover. The farm characteristics affected the N balance.

N input

CF had higher N input in all farm pairs (Fig. 3) compared to OF (CF: 265 kg N ha^{-1} a^{-1}, OF: 158 kg N ha^{-1}a^{-1}). The results of N input, N output, N efficiency and N balance are presented in Table 3.

One main factor influencing the N balance was the difference in fertilizer application and N input between organic and conventional farming. N input differed in quality, quantity and timing. The most important N inputs in organic farming systems were organic fertilizers and symbiotic N$_2$ fixation. The most important factor in conventional farming was the use of mineral N fertilizers. OF was largely dependent on manure as an N input.

N input from organic fertilization was higher in both DF systems. In DF, N from organic fertilizers
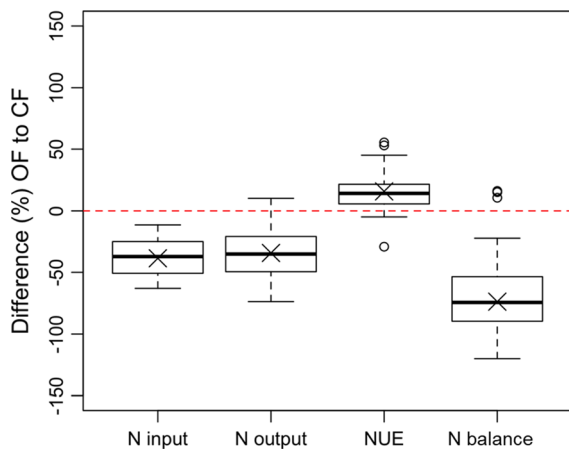
Fig. 3 Comparison (%) of nitrogen (N) input, N output, N-use efficiency (NUE) and N balance between organic and conventional farming (OF, CF). Boxes denote 25th and 75th percentile, whiskers denote 25th/75th percentile $\pm$ 1.5 $\times$ Inter Quantile Range (IQR), outliers are above/below 25th/75th percentile $\pm$ 1.5 $\times$ IQR, lines denote median and crosses denote mean values

amounted to 134 kg N ha^{-1} a^{-1} in CF, and to 91 kg N ha^{-1} a^{-1} in OF. Additionally, in CF mineral fertilizer (91 kg N ha^{-1} a^{-1}) was applied. However, conventional DF applied less mineral fertilizers than the arable farms (158 kg N ha^{-1} a^{-1}). It can be assumed that the farmers in conventional DF had taken the N input from organic fertilizers into account. The moderate N balances implied this. Considering all farming systems, the yearly average total N input, including atmospheric deposition, symbiotic N$_2$ fixation and fertilizers, was 65% higher in CF (266 kg N ha^{-1} a^{-1}) than in OF (161 kg N ha^{-1} a^{-1}). Moreover, total N input was distributed differently between symbiotic N$_2$ fixation and organic and mineral fertilization for OF and CF. N input in OF ranged from 97 to 240 kg N ha^{-1} a^{-1}, in CF from 177 to 344 kg N ha^{-1} a^{-1}. Mean total N$_2$ fixation integrated over the whole crop production system in OF and CF was 49 and 14 kg N ha^{-1} a^{-1}, respectively. In OF, N$_2$ fixation amounted to 30% of total N input in arable as well as dairy farms, whereas in CF it was much lower (1% and 7%, respectively). Conversely, N input from organic fertilization was higher in both dairy farming systems and amounted to 91 kg N ha^{-1} a^{-1} on organic and 134 kg N ha^{-1} a^{-1} on conventional farms. The mean N input from mineral fertilizer in CF was 118 kg N ha^{-1} a^{-1}. On conventional dairy farms, N input from mineral fertilizers (91 kg N ha^{-1}

a^{-1}) was lower than on arable farms (158 kg N ha^{-1} a^{-1}), due to slurry application.

N output

90% of organic farms had lower N output than their neighbouring conventional farms, ranging from 94 to 236 kg N ha^{-1} a^{-1} (Table 3). N output varied more than N input and NUE (Fig. 3). 7% of organic farms had an N output comparable with conventional farms. N output of conventional farms ranged from 155 to 310 kg N ha^{-1} a^{-1}. Independent of farming type, the yearly average N output was 50% higher in CF (208 kg N ha^{-1} a^{-1}) than in OF (146 kg N ha^{-1} a^{-1}).

Generally, N output was lower on the arable farms. The highest output (222 kg N ha^{-1} a^{-1}) was found in conventional DF. The organic DF achieved quite similar (no significant difference) N output (166 kg N ha^{-1} a^{-1}) to conventional AF (186 kg N ha^{-1} a^{-1}). On the other hand, organic AF had low levels of yield and N removal (116 kg N ha^{-1} a^{-1}). In organic DF, the high proportion of grass-clover is related to high yields and N removal, while in organic AF grass-clover is used mainly for green manuring (no yield). N output was affected by yield potential of the site, crop rotation, crop yield, protein content of products, N uptake by crops and yield utilization (straw, green manure etc.).

NUE

In 97% of the farm pairs, the organic farms were as efficient as or more efficient than the conventional farms. The mean value of NUE (without Δ SON) in organic farming amounted to 91% and in conventional farming to 79%.

Organic dairy farms were the most efficient (mean 95%), ranging from 83 to 121%. For low levels of N input, NUE was higher than 100% implying a depletion of soil N stocks. Higher efficiency is consistently associated with lower environmental impacts and an N balance close to zero. The lowest NUE was recorded on conventional arable farms (mean 77%). Further, the average NUE of organic arable farms was 83%. NUE of conventional dairy farms amounted, on average, to 80%.

Table 3 Soil surface nitrogen (N) balance—N input, N output, N-use efficiency (NUE) and N balance in crop production systems of arable and dairy farms, mean values for the years 2009–2011

Parameter	Unit	Organic farming system		Conventional farming system		Mean	P
		Arable farm (n = 12)	Dairy farm (n = 18)	Arable farm (n = 12)	Dairy farm (n = 18)		
Total N input	kg N ha^{-1} a^{-1}	142[a]	173[a]	246[b]	280[b]	214	***
		(97–185)	(118–240)	(177–313)	(205–344)		
N$_2$ fixation	kg N ha^{-1} a^{-1}	44[a]	52[a]	3[b]	21[c]	31	***
		(30–58)	(25–101)	(0–13)	(5–64)		
Organic fertilizer	kg N ha^{-1} a^{-1}	37[a]	91[b]	26[a]	134[c]	80	***
		(3–88)	(27–144)	(0–79)	(50–237)		
Mineral fertilizer	kg N ha^{-1} a^{-1}	0[a]	0[a]	158[c]	91[c]	59	***
				(103–222)	(0–218)		
Straw, green manure	kg N ha^{-1} a^{-1}	38[b]	10[a]	37[b]	11[a]	21	***
		(14–72)	(0–24)	(18–60)	(0–37)		
Seed	kg N ha^{-1} a^{-1}	3.4[c]	1.3[ab]	2.3[bc]	1.1[a]	1.8	***
		(1.9–5.6)	(0–3.4)	(1.3–7.8)	(0–2.4)		
N deposition	kg N ha^{-1} a^{-1}	20	20	20	20	20	
N output	kg N ha^{-1} a^{-1}	116[b]	166[a]	186[a]	222[c]	175	***
		(94–139)	(110–236)	(155–210)	(173–310)		
Δ SON	kg N ha^{-1} a^{-1}	3[ab]	13[b]	− 14[a]	− 4[a]	0	***
		(− 25–16)	(− 3–47)	(− 58–19)	(− 43–32)		
N balance without Δ SON	kg N ha^{-1} a^{-1}	26[a]	8[a]	60[b]	58[b]	37	***
		(− 4–72)	(− 41–34)	(15–110)	(− 37–124)		
N balance with Δ SON	kg N ha^{-1} a^{-1}	23[a]	-5[a]	74[b]	62[b]	37	***
		(− 3–62)	(− 41–34)	(28–111)	(− 37–129)		
NUE without Δ SON	%	83[a]	95[b]	77[a]	80[a]	85	***
		(61–104)	(83–121)	(62–92)	(61–114)		

Units in parentheses represent minimum and maximum values, respectively. *P*—probability value was calculated using the F-test. Differences between farm types denoted by the same letter (a–c) were not significantly different at the 0.05 probability value calculated by post-hoc comparisons using the Tukey HSD test, ***$p < 0.001$. Δ SON means accumulation or depletion of soil organic nitrogen

N balance

N balance without Δ SON was lower in 90% of organic farms and ranged from − 41 to 72 kg N ha^{-1} a^{-1}. In only 10% of the organic farms, the N balance was higher than on conventional farms, where it was between − 37.0 and 124 kg N ha^{-1} a^{-1}. The yearly average N balance was four times higher in CF (59 kg N ha^{-1} a^{-1}) than in OF (15 kg N ha^{-1} a^{-1}).

The conventional arable farms did not have N deficits. N balance with Δ SON amounted to 23 and − 5 kg N ha^{-1} a^{-1} on organic arable and dairy farms, respectively. In conventional farming, the N balance with Δ SON was 74 kg N ha^{-1} a^{-1} for arable farms and 62 kg N ha^{-1} a^{-1} for dairy farms. N balance without Δ SON was higher in organic farming than N balance with Δ SON (DF: 26 kg N ha^{-1} a^{-1}, AF: 8 kg N ha^{-1} a^{-1}). In CF, N balance without Δ SON was lower than N balance with Δ SON (DF: 58 kg N ha^{-1} a^{-1}, AF: 60 kg N ha^{-1} a^{-1}).
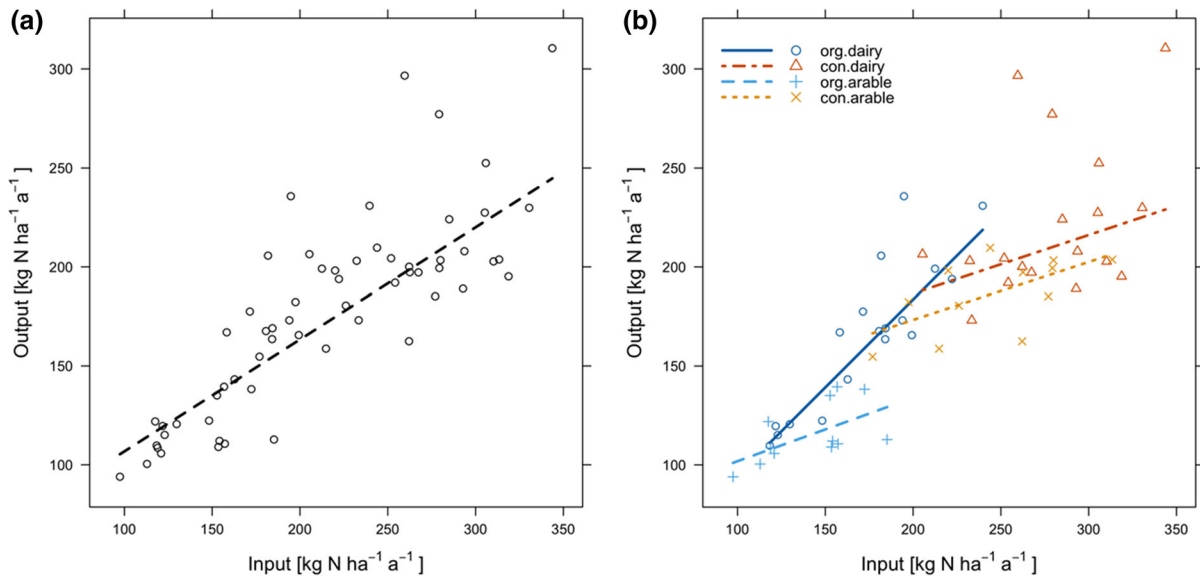
Fig. 4 **a** Overall relationship between nitrogen (N) input und N output and **b** relationship differentiated according to farming system
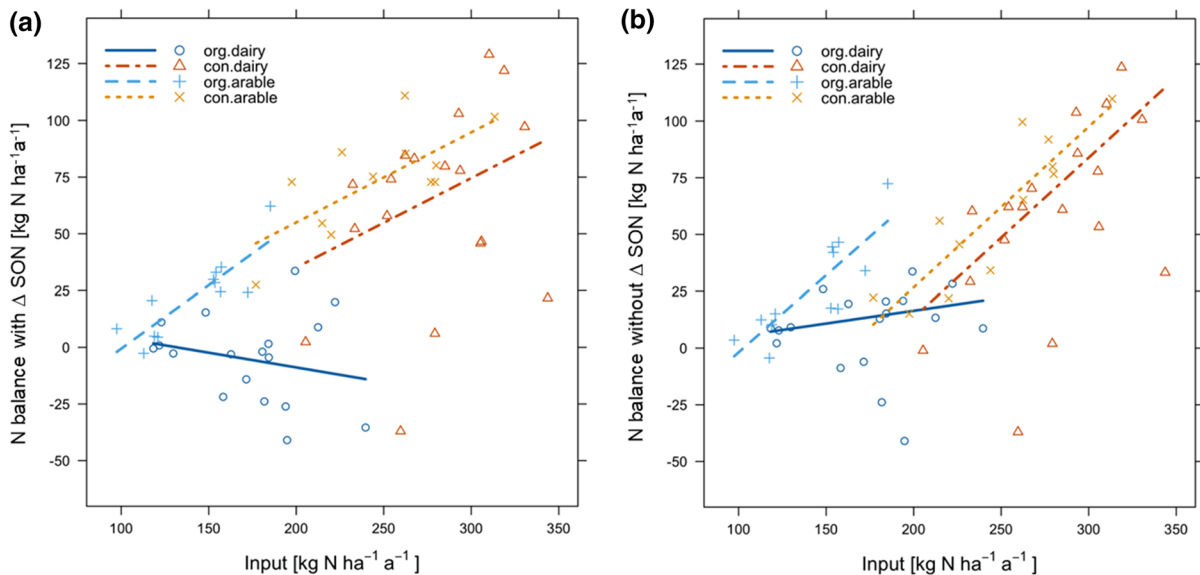

Fig. 5 Farming system-specific relationship between nitrogen (N) input und N balance **a** with accumulation or depletion of soil organic N (Δ SON) and **b** without Δ SON

The relationships between N parameters

Figures 4, 5 and 6 show the relationships between N input and N output, NUE and N balance. The correlation between these parameters changed according to farming system. Increasing N input in organic dairy farming increased N output much more in comparison to the other farming systems (Fig. 4). In

CF, there was high variability in N output. Hence, similar N input yielded different outputs. This can be caused by different site conditions, different fertilizations and management systems. In DF, a large increase in N outputs was found with increasing N input (Fig. 4b). Apparently, the cultivated crops (forage plants, grassland) had a high yield and N removal potential, which can be utilized by increasing N
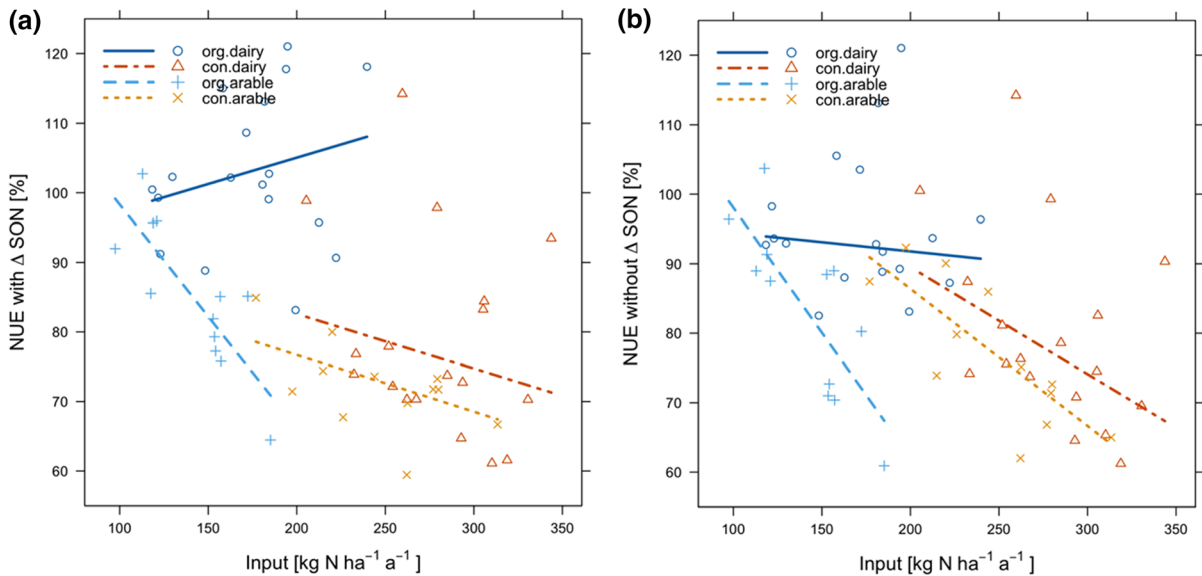
Fig. 6 Farming system-specific relationship between nitrogen (N) input and N-use efficiency (NUE) **a** with accumulation or depletion of soil organic nitrogen (Δ SON) and **b** without Δ SON

fertilization. Therefore, the N balances remained unchanged or increased only negligibly (Fig. 5b).

Organic dairy farming showed only small changes in N balance (with/without Δ SON) with increasing N input (Fig. 5) in comparison to the other farm types. Generally, the NUE (with Δ SON) of the organic dairy farms increased with increasing N input. Further, the NUE (without Δ SON) of the organic dairy farms decreased more slowly with increasing N input compared to the other farm types (Fig. 6). In CF, with increasing N inputs (from 200 to 350 kg N ha^{-1} a^{-1}), the N balances rose from below 25 to over 100 kg N ha^{-1} a^{-1} and the NUE decreased from 90 to 65% (Fig. 6b).

Discussion

N fluxes in farming systems are complex

Organic and conventional farming systems use N differently and from different sources. Therefore, the N fluxes of the systems are different. N fluxes of farming systems are extremely complex. They differed not only between the organic and conventional systems, but also within the farm types (AF and DF). Some of these N fluxes can be exactly (or very precisely) quantified, e.g. the mineral N input and N output in the products sold by the farm. Other N fluxes can be calculated only approximately, e.g. the N$_2$ fixation by legumes. This resulted in errors in the N balance, which must be taken into account when interpreting the results.

Many studies (Benincasa et al. 2016; Migliorini et al. 2014; Stenberg et al. 2012; Thorup-Kristensen et al. 2012) were conducted at the field and crop levels. However, farming systems are a complex, and in order to evaluate and compare these systems, research at the farm level is needed. In many experiments, fertilizer application rates differ from those used on farms. Further, some simplifications were made, such as using the same crop rotations in OF and CF. However, our results (Table 1) showed huge differences in farm characteristics. This suggests that some results of field experiments are quite different to what happens in practice and considerable errors in the interpretation of results may have arisen.

Our results for the soil surface nitrogen balance (Fig. 2) from 30 pairs of neighbouring farms in Germany, derived by using the uniform and detailed method REPRO (Küstermann et al. 2010), show considerable heterogeneity between farming systems. The enormous variability of N balance results (OF and CF, AF and DF) was caused by different site conditions (e.g. yield potential), very different farm structures (crop rotation, livestock, see Table 1), but

was also due to the influence of the farmer and farm management (Sanders and Heß 2019). These differences suggest possibilities and ways of improving the N management of these farms.

The problem of studying N balances at the farm level is that they cannot be replicated because of specific farm conditions. This limits the possibilities for extrapolation of results to other farms. Generally, the comparison of balances is only valid when the environmental covariates are similar. Consequently, the climate and soil conditions of the compared farms were similar. Nevertheless, data on the prevailing soil type, annual precipitation and average temperature on the farms were taken into account (analysis is not shown) for the evaluation of the NUE in this context. Generally, the data showed lower NUE for farms with sandy soils and a positive effect of precipitation on NUE.

However, our results describe the soil surface N balance only. Defining limits is important because the soil surface balance does not take into account all parameters (e.g. N inputs from biomass and feed purchase, N flows and N emissions from animal husbandry, ammonia emissions from the housing system, see Fig. 2) like a farm-gate balance does. However, the usefulness and reliability of whole-farm balances and of N indicators strongly depends on their completeness and the availability of data, as suggested by Schröder et al. (2003) and by Quemada et al. (2020). Nevertheless, inherent uncertainties are usually smaller for a farm-gate balance than for a soil surface or a soil system balance (Oenema et al. 2003).

N input and organic fertilizers are challenging

The most influential factor in the N balance is the N input. In our study, N input in the organic farming systems was 40% (AF: 42%, DF: 38%) lower than in the conventional systems. In France, Benoit et al. (2014) showed a difference of only 20% in N input between conventional and organic AF. The large differences in N input recorded on the pilot farms do not have to be the same in other regions of the EU. One reason for the large differences in Germany is the high level of fertilization and intensive use of external resources in conventional agriculture. Further, there are differences in the proportion of N_2 fixation in OF. Watson et al. (2002) also estimated that 62% of the N inputs were derived from N_2 fixation, in a review of 47

European organic dairy farms (mainly Sweden and Austria). In the dairy farms in Germany, the proportion of N_2 fixation was lower (31%). Thus, it is important to note the country where the studies took place because of differences in climatic and technical conditions and regional crop rotations. Each site has an individual yield potential. Furthermore, N input is often higher in Western Europe than in Central Europe (van Grinsven et al. 2015). This is caused by higher intensity farming systems (high input systems) and concentrated animal husbandry related to high stocking rates and manure use. The consequence is a high amount of slurry delivering N that cannot be used by the plants. Many N-related environmental problems in Germany could be solved if mineral N fertilizer applications were adapted to the nutrient requirements of crops, in addition to more accurately taking into account fertilization with organic fertilizers. In OF the livestock density is limited to 1.4 LU per ha by organic farming associations (Bioland, Naturland, Demeter), and to 2.0 LU per ha for non-member EU organic farming, and the purchase of feed is also limited. This restricts the production of organic fertilizers. Additionally, mineral N cannot be used in OF.

According to Duncan et al. (2019), Möller (2018) and Powell et al. (2010), N inputs via organic amendments are a key factor characterizing and improving the efficiency of CF. On farms, application rates of manure are often based on fully exhausting the maximum legal input, which is much higher than the amount of N fertilizer that would have to be applied to supply total plant-available N from an agronomic perspective (Han et al. 2017; Haneklaus et al. 2016). N excess arises mostly with monogastric (pig, poultry) livestock farming because of higher livestock and feed acquisition and higher slurry production (Häußermann et al. 2020; Velthof et al. 2000).

The pilot farms were arable and dairy farms (no farms with monogastric animals) that are more limited to the available farmland. Therefore, stocking rates, the use of organic fertilizers, and ultimately the N balances of the farms are at a moderate level, much lower than the mean value in Germany. Higher balances can be expected on farms with monogastric animals. Correctly including organic fertilizers in the calculation of N balances is also challenging. For example, Godinot et al. (2014) were working on the status of manure. They considered manure to be a by-product of animal production and not as a final product

for further use. It can be concluded that the status of manure varies from a waste to a highly valuable resource (organic fertilizer in intensive crop regions with low soil organic matter).

Commonly, N balance is calculated without accounting for accumulation or depletion of soil organic N. However, Yang et al. (2016) showed that applying organic manure to cultivated farmland significantly increased the soil C and N accumulation rates, and this was intensified when was combined with mineral fertilizer. Taking into account changes in soil N decreased N balance in OF and increased N balance in CF. The accumulation or depletion of soil organic N (Δ SON) was taken into account to quantify N losses more precisely and to enable a fair system comparison between OF and CF. Organic fertilizers contain a considerable proportion of organically-bound N, which initially leads to soil N accumulation, but becomes available to plants in the long term after mineralization. If Δ SON were not taken into account, the N loss in OF would be overestimated (Lin et al. 2016).

Lower output in OF: balancing environmental benefits and yield improvement

In our study, N output from organic farms was lower than from conventional farms. For dairy farms, the output in OF was 75% of the output in CF, for arable farms it was only 62% of the N output in CF. This yield gap is often discussed when comparing both systems. Seufert et al. (2012) found that average yields in OF were 25% lower than yields in CF. Nevertheless, there is large variation between the yields of different crops. For example in Austria, with climate and soil conditions similar to Germany, the OF yield level for cereals was 59–77% and for soybean 93% (Brückler et al. 2018), and for grassland 90% (Seufert et al. 2012). Therefore, OF requires more land to produce the same amount of products. Nevertheless, OF has shown better resilience and higher yield stability (Seufert and Ramankutty 2017), which is becoming increasingly important due to climate change. In the Netherlands, Schrama et al. (2018) reported that, over time (13 years) on sandy loam soil, the yield gap between OF fields based on farmyard manure and CF fields (based on applying pig slurry and mineral fertilizer) declined strongly, excluding years with *Phytophthora* outbreaks in potato.

As suggested by Foley et al. (2011), closing yield gaps by reducing the unsustainable use of water, nutrients and agricultural chemicals will require new approaches, such as the combination of practices from organic and conventional agriculture and solutions from precision agriculture. In conventional farming, higher input corresponds to higher yield. According to our results, OF is more N efficient and with higher input, output (yield) can be increased. What we found is that organic DF, in comparison to organic AF, had higher N inputs (more available fertilizer), higher yield and N output, higher SON enrichment, lower N balance and higher NUE. The multi-faceted mixed farms with closed nutrient cycles represent an ideal OF system. Specialized AF achieve neither the yield level nor the N efficiency of these farms. However, the trend in the past few years has been towards specialized AF without livestock, mainly due to (short-term) economic advantages (Sanders 2019).

Generally, N input correlated with N output. Many authors have tried to explain how parameters correlate to help improve N fluxes. For example, Pandey et al. (2018) suggested that the difference in N output between organic and conventional farming could not be explained by the application rate and type of N inputs only. Instead, there are other factors, such as disease and pest damage, competition with weed species and inadequate nutrient supply (Nguyen et al. 1995), that need to be considered. In France, Anglade et al. (2015) estimated that there was no significant reduction in N output when OF received 12% less total N inputs compared to CF, while the N balance in OF simultaneously decreased by 26%. This suggests that with lower intensity and fertilization level in CF, other relationships also influence the N balances. On the other hand, in the DOK long-term systems experiment in Switzerland, doubling the organic fertilization in OF improved wheat grain yields by only 13% and 19%. Mayer et al. (2015) explained the slight improvement in yield with integrating system effects that affected the farming systems in highly fertile Loess soils. The relatively low yield differences, in spite of large input differences between organic and conventional farms, can indicate low crop response to fertilizers or a lower utilization of N mineralized from soil and manure (Halberg et al. 1995; Refsgaard et al. 1998). The N output is not only affected by the harvested biomass, but also by N uptake of the entire crop rotation. Different crop types require different

fertilizer amounts, have different N uptakes and after harvest leave different amounts of N in the soil. For this reason, it is important to take into account the entire crop rotation, not only individual crops. Further, main and secondary crop utilization (e.g. straw and green manure, legume-grass mixture) plays an important role. Combining crops spatially and temporally can promote efficient nutrient use (Wilkins 2008). Still, green manure has a high loss potential in organic arable farming.

More efficient: more environmentally friendly

The NUE of the studied farms was higher in OF than in CF. Migliorini et al. (2014) showed similar results from a long-term experiment in Italy. NUE differed according to farm type in organic farming. The highest NUE was estimated for organic dairy farming. This is in accordance with Swain et al. (2014), who concluded that the combination of legumes (or their mixtures) and livestock increased the NUE and simultaneously reduced N losses. Oomen et al. (1998) also described the favourable N balance of dairy farms. The NUE of arable farms (OF: 83%, CF: 77%) was lower than the NUE of dairy farms (OF: 95%, CF: 80%). In France, Benoit et al. (2014) reported results in a similar range for arable farms, although inverted for OF (78%) and for CF (81%). This difference is caused by higher N input in OF and lower N input in CF (difference 20%) in comparison to our farms (difference 42%).

CF used more mineral fertilizers and less cover crops. According to the German Fertilizer Ordinance, N input should be decreased. However, it is doubtful whether in CF systems a reduction would also decrease N removal. The use of cover crops reduced and replaced N fertilization. Cover crops can decrease N losses through N leaching. However, there are different legume, non-legume and legume–non-legume mixtures used as cover crops. In general, cover crops have the potential to reduce N_2O emissions when legumes are not used and their residues are not incorporated into the soil (Abdalla et al. 2019; Basche et al. 2014). Some cover crops can even increase yields and also contribute to the control of weeds, pests and diseases.

The balance on conventional arable and dairy farms was lower than 70 kg N ha^{-1} a^{-1} and lower than the German average (93 kg N ha^{-1} a^{-1}, BMEL 2020). This suggested that the pilot farms performed better

than average German farms. Nevertheless, the large N surplus of a few farms suggests some inefficient management practices. To increase efficiency, several strategies can be used, e.g. precision farming with temporally- and spatially-adapted application of N according to crop requirements. This shows that it is also possible for conventional farms to have a low N surplus. On arable farms, N balance was higher than on dairy farms; the latter farms differed in area-related livestock numbers and crop rotation composition. On organic dairy farms, the N balance was lower because of soil organic carbon and N accumulation. Diversified crop rotations and organic N fertilizers in OF improved N retention more than strategies like reduced N application rates, nitrification inhibitors and changing the type of mineral fertilizer used (Gardner and Drinkwater 2009).

Effective application preserves resources. It has been suggested that OF is more environmentally friendly and sustainable. Pimentel et al. (2005) reported an increase in soil N stock after 20 years in OF on dairy as well as arable farms. However, in CF the soil N remained unchanged. Further, Gattinger et al. (2012) suggested that soil organic carbon increased in OF. Besides reducing N input, N surpluses can be reduced by increasing C availability, which supports the internal biological mechanisms for N storage (Blesh and Drinkwater 2013). The microbial community is able to change organic N into mineral N (Lori et al. 2017). Avoiding N losses and preserving soil fertility is thus not only important for the environment, but is of economic interest to farmers as well.

Conclusion

The aim of this paper is to compare N soil surface balance in OF and CF, analysing system-related differences between AF and DF (farm characteristics and N input).

In CF, with N inputs increasing from 177 to 344 kg N ha^{-1} a^{-1}, the N balances rose from below − 37 to over 129 kg N ha^{-1} a^{-1} and the NUE decreased from 90 to 65%. Further research is hence needed to clarify whether the high level of N fertilization can be maintained in this way in the future or whether greater restrictions on N input are necessary. There are various ways N input can be

reduced, from stricter legal regulations in fertilizer ordinances to precision farming technologies (e.g. sensor-based systems and algorithms for site-specific N fertilization).

In OF, N inputs (97–240 kg N ha^{-1} a^{-1}) and N balances (− 41–62 kg N ha^{-1} a^{-1}) were significantly lower than in CF. Generally, further expansion of OF area, e.g. to 20% (German Sustainable Development Strategy) or even 25% (EU farm-to-fork strategy) would lead to a reduction in N balances, which has not yet been achieved. However, this effect will increase as the area of farmland farmed organically increases.

Optimisation is also necessary in OF. On farms with negative N balances and decreasing soil N stocks, the N inputs should definitely be increased, e.g. by higher N$_2$ fixation capacities of the legumes in the crop rotation, purchase of fertilizers, inter-farm nutrient recycling (e.g. feed-manure cooperation). Negative N balances are not sustainable because decreasing soil N stocks will finally lead to decreasing yields.

In DF, a large increase in N outputs was found with increasing N input. Apparently, the cultivated crops (forage plants, grassland) had a high yield and N-removal potential, which can be utilized by increasing N fertilization. Therefore, the N balances remained unchanged or increased only negligibly. Our results show that the organic DF, in comparison to organic AF, had better N balances (higher yields and N removal, higher soil N accumulation, lower N balances, higher NUE). Although there is a trend towards specialized organic AF, it is more likely that agriculture will be sustainable by maintaining and promoting DF.

Our results therefore also reflect the great importance of the basic principle of organic farming—closed nutrient cycles the system soil—plant—animal—soil.

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