Nutr Cycl Agroecosyst
https://doi.org/10.1007/s10705-023-10297-7

ORIGINAL ARTICLE

Sustainable growth of organic farming in the EU requires a rethink of nutrient supply

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Received: 27 January 2023 / Accepted: 22 June 2023

Abstract The European Commission recently set a target of increasing the area of organic agriculture to 25% by 2030. To achieve this, it is imperative to understand current nutrient use patterns and identify sustainable nutrient supply opportunities. To that end, this study assessed the sustainability of the current nutrient origin and supply of 71 arable organic farms in 8 European regions. Deficient nutrient supply was found on 24%, 66%, and 56% of farms for nitrogen, phosphorus, and potassium, respectively. On average, we show a moderate surplus for nitrogen (28 kg ha^{-1}), while phosphorus and potassium balances were close to zero (– 1 and 2 kg ha^{-1}, respectively). Large variation between countries and farm types shows a divide between more intensive systems relying on external inputs, and less intensive systems facing nutrient deficits and lower outputs. We show, for the first time, the extent of current use of external input types, where conventional manures supplied 17–26% of external nutrients and inputs from non-agricultural origin supplied 31–41%. A large proportion of nutrient sources within the last group are materials derived from urban

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Marie Reimer and Myles Oelofse have shared first authorship.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10705-023-10297-7.

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wastes. The sustainable expansion of the organic sector will require increased use of locally available recycled fertilizers from urban wastes, and acceptance of such sources by organic farmers is shown to be high, provided they are considered safe.

Keywords Organic agriculture · Sustainable nutrient management · Farming systems · Nutrient use · Contentious inputs · Nutrient demand · Recycling · Efficiency

Introduction

An increase in organic agriculture to 25% of total farmland by 2030 is part of the Farm to Fork (F2F) strategy of the European Commission (EC) (European Commission 2020). Sustainable soil fertility management requires that, in order not to deplete soils, nutrients removed from the system in harvest shall as a minimum be replaced. In organic systems, soil fertility and biological activity should be maintained and increased by multiannual crop rotations, including biological nitrogen fixation (BNF) by leguminous plants, and by the application of livestock manure or organic material, preferably sourced from organic production.

Although organic agriculture in principle seeks to decrease reliance on external nutrient sources by closing farm nutrient cycles, provision is made for the use of certain other external inputs (European Commission 2018), and commercial organic farmers, operating in open systems with nutrient exports, invariably require external nutrient inputs (Möller 2018). A key concern is that some external products can originate from systems with significant environmental or animal welfare impacts—aspects that are contrary to the principles of organic agriculture (IFOAM 2017). Reliance on nutrients derived from conventional sources may thus be seen to pose a risk to organic farming—and the future use of and reliance upon what is termed “contentious input” may become a technical and/or regulatory limitation for future growth (Beck et al. 2014).

The expansion of organic farming in Europe, from 9.1% of total EU agricultural land in 2020 (Eurostat 2023) to 25% by 2030, will require careful consideration regarding how to ensure a sustainable nutrient supply to organic farms in the future, particularly in specialized, arable, and mixed farming systems where nutrient limitations or imbalances are common (Reimer et al. 2020c; Cooper et al. 2018; Möller 2018). While increased BNF is an option to ensure nitrogen (N) supply to a certain extent, it would demand a greater land allocation to leguminous crops, thus potentially competing with other crops or land-uses (Döring and Neuhoff 2021). Barbieri et al. (2021) found that future expansion of organic farming may be accompanied by a marked N deficit in many regions of the world. Beyond increasing N from legumes, the potential to increase the supply of N and other important nutrients using external inputs in organic farming faces several dilemmas. Firstly, the optimal resource utilization of societal waste streams is limited by current organic regulations, and secondly, a potential restriction on the use of contentious inputs may limit future nutrient supply (Løes and Adler 2019).

The number of direct assessments of reliance of organic farms on conventional nutrient sources across Europe is limited, with work suggesting high reliance of organic farms, especially stockless ones, on animal manure from conventional farms (Foissy et al. 2013). Measures to ensure a sustainable nutrient supply in organic systems in Europe demand a broader understanding of the extent of reliance of organic agriculture on such inputs. Furthermore, external input use must be assessed in concert with an organic farm’s nutrient balance, which provides an indication of the sustainability of nutrient supply. In this paper, we assessed current nutrient management strategies and practices from a selection of organic farms in eight European regions, and the extent to which they sufficiently fulfil farm nutrient requirements. We furthermore assessed the current use of external nutrient inputs in arable and mixed organic farming systems, focusing on the extent of reliance of organic farms on ‘contentious’ nutrient inputs, and the relationship to farm outputs. The study discusses which opportunities may be available for the sector to ensure a sustainable future nutrient supply for organic systems.

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Methodology

The study utilized a multiple case study methodology, comprising of 71 farm cases in eight regions in seven European countries (DK = Denmark, EST = Estonia, HU = Hungary, UK = United Kingdom, ITA = Italy (Apulia), SUI = Switzerland, GER N = Northern Germany (Lower Saxony), GER S = Southern Germany (Bavaria). In Germany, two regions were assessed due to their contrastingly organic farming systems. Regions were selected to represent a diversity of organic farm types across Europe.

In-region farm selection

The research team consisted of workers involved in the organic sector in each of the study regions with insight into the specific country's organic sector. The selection of farms was undertaken by the in-region expert. A central hypothesis driving farm selection was that stockless and low animal density farms would exhibit the strongest reliance on external nutrient inputs, therefore such farm types were targeted insofar feasible. The aim was not to achieve a representative sample of all organic farms in each region. Instead, we sought to select farms that represented typical cropping systems and would provide general insight into the current conditions at the farm scale in each region. In each region, a target of ten farms was set, and farms were selected utilizing in-country partner's networks. Given the extent of data and time required from each farm, a key challenge experienced was the willingness to participate, sometimes dictated by issues of trust, and the target was not met in most regions. It is therefore imperative that the results from the specific case regions are critically assessed in terms of what can be generalized due to the contextual implication of farm-level specifics.

Further, farms were sorted into farm types depending on their livestock density is determined by livestock unit (LU) per ha to allow analysis based on farm type. The following four farm types were defined: stockless < 0.1 LU ha^{-1}, low stocked $[0.1 \text{ LU ha}^{-1} < x < 1.0 \text{ LU ha}^{-1}]$, and high stocked > 1.0 LU ha^{-1}.

Data collection

Evaluation of nutrient management practices was conducted by analysing farm gate nutrient balances for participating organic farms. Farm gate nutrient balances have been proven as an appropriate tool to evaluate the nutrient supply of an organic system (Reimer et al. 2020c; Watson et al. 2002). The balances focused only on external inputs and outputs. Nutrient balances were created based on survey data collected using an extensive questionnaire, which was completed through personal interviews. The questionnaire collected information about farm nutrient inputs, crops cultivated and outputs for a three-year period (2015–2017). The questionnaire (Supplementary Material I) furthermore included questions about farmers views of the acceptability of various types of external inputs. Validation of data and collection of additional contextual data was done through interviews following first round of data analysis.

Farm characteristics

In all, the sample consisted of 71 organic farms across eight regions (Table 1). Mean farm size was largest in Estonia, whilst mean farm sizes were considerably smaller in Italy and Switzerland. The farms engaged in this study have all been organic, on average, for a substantial period. Italy has the lowest mean number of years under organic management (9) and the UK has the highest (24).

The farms of each region and farm type also differed in terms of their area dedicated to certain crops (Supplementary Figure 1). For farms with a higher livestock density there were higher percentage of land dedicated to pasture and fodder legumes. Over all farms 36% were under pasture or fodder legumes and grassland mixtures, while highly stocked farms had 61%, low stocked farms 43%, and stockless farms about 19%. On study region average, CHE showed the highest share of pasture and fodder legumes or grasses with about 60% while it was lowest for ITA with about 5%. Grain legumes or grain legumes mixtures were only cropped on 15% of the area overall. Yet, here stockless farms had higher amounts of grain legumes (20%) than low stocked farms (13%) or even highly stocked farms (6%). Among the study regions there are also some differences. While EST shows the highest amount of grain legumes and grain

Table 1 Overview of the organic farms in each case area

Country	Farms	Ave farm size (ha)	Ave stocking rate (LU ha^{-1})*	Ave years organic**	Farming system types
Denmark	7	117.0 (13.8–321.7)	0.6 (0.1–2.3)	18.2 (8–31)	Arable (3). Mixed (4)
Estonia	11	402.7 (163.8–615)	0.2 (0.1–0.42)	15.2 (8–23)	Arable (6). Mixed (5)
Hungary	10	98.0 (7.2–243.0)	2.0 (1.6–2.4)	14.9 (6–16)	Arable (8). Mixed (2)
United Kingdom	8	265.4 (20.9–1163.3)	1.5 (0.9–2.8)	24.0 (19–34)	Mixed (8)
Italy	5	27.1 (5.2–42.5)	0	9.0 (1–22)	Arable and vegetable (5)
Switzerland	10	20.9 (7.6–37-3)	1.3 (0.7–2.2)	20.8 (10–30)	Arable (3). Mixed (7)
Germany (N)	10	160.2 (24.4–422.0)	0.4 (0.1–0.9)	18.0 (5–36)	Arable (6). Mixed (4)
Germany (S)	10	60.1 (15.0–125.0)	0.6 (0.4–0.7)	22.6 (10–32)	Arable (6). Mixed (4)

Numbers in parenthesis for farm size, stocking rate and years organic present the range of values; for farming system type they show the count for each farm type. LU = livestock unit

*Average is for mixed farms only, **As of 2019

legume mixtures with 26%, CHE, DNK,GER S, and HUN have between 9 and 17%, and ITA, and UK have about 5–7%. A sole characteristic of ITA is the high share of orchards and grapes (39% and 12%, respectively).

Estimation of farm gate nutrient balances

Farm gate nutrient balances are partial nutrient balances where the farm gate border is set as the system boundary. Inputs and outputs related to the identified flows were quantified, and the deficit or surplus was calculated using the formula ∑Outputs—∑Inputs. Inputs into the system quantified were organic fertilizers, either unprocessed or processed; feed; animal entries; straw; and BNF. For Germany and Switzerland, seed was included as an input. Due to limited data availability this was not possible for the other regions. Other inputs such as extracts and mineral supplements for animals were included as system inputs if they contained NPK. Outputs were sales of crop and animal products, and crop residue or organic material removal from the farm. Balances were calculated for N, P and K as these are the main nutrients deliberately managed by farmers. Nutrient flows were quantified on a per hectare basis and are presented on a per annum basis, averaged over the three-year period (2015–2017). A modified version of the "NutriGadget" tool (online available at https://orgprints.org/38025/) was used for the calculation of the farm gate budgets (Reimer et al. 2020b).

Input and crop nutrient contents were obtained mainly from standard values in the literature, including Möller and Schultheiß (2014), product descriptions, scientific and grey literature, in-country norms and national databases. A detailed list can be found in the supplementary material of Reimer et al. (2020a). Nutrient flows not included in the nutrient balance calculation were inputs from atmospheric deposition and sedimentation; outputs from leaching losses, gaseous N losses, and erosion were not accounted for. Nutrient loss estimation is depending on many management and climate factors and associated with high uncertainties therefore they are only addressed in a more general way in the evaluation of the resulting balances (Hansen et al. 1999; Schmidt et al. 2008).

Biological nitrogen fixation quantification

The amount of N entering the system through BNF was estimated using an approach which was dependent on the type of data available. Where yield information for N fixing crops was recorded by the farmer, standard literature values for N derived from the atmosphere (N_{dfa}) were utilized. Yield information for all legumes was provided by the farmers for all the German and Swiss cases, and the amount of N input from BNF was assessed for each crop type individually and yield-dependently, as suggested by Bachinger et al. (2013) for grass-clover and by Kolbe (2008) for all other crops similar to Reimer et al. (2020b). However, in many cases, farmers did either not record yield (as the crop was used as feed or for internal nutrient cycling purposes), or the crop was ploughed into the soil as a green manure. In such cases, we only had the area of the crop, and therefore utilized an estimate of *N* fixed per hectare based on literature values. Methods used for estimation of *N* input via BNF are presented in Supplementary Table 1.

Analysis of nutrient flows and nutrient balance

Aggregated farm nutrient balances were calculated for each country and farm type. The proportion of *N* derived from BNF of total *N* inputs was also calculated. A farm-level efficiency indicator was calculated for each nutrient, by dividing the nutrient output by the nutrient input.

To assess organic farms utilization of inputs which may be of ‘contentious’ origin, the proportions of external input inflows for N, P and K (in kg nutrient inflow ha^{-1}) for different categories of inputs was calculated. In this study, inputs from conventional farms, especially animal manures, and finite resources such as rock phosphate, were considered ‘contentious’ inputs. The categories were: (1) Feed; (2) Conventional manures (in any form derived from conventional farms); (3) Organic manures (in any form derived from organic farms); and (4) Inputs of non-agricultural origin (organic inputs other than from direct agricultural provenience, many products derived from urban and food industry waste like household waste compost).

Statistical analysis was carried out using the *R environment for statistical computing* (R Core Team 2022). The influence of BNF, livestock density, and study region on the nutrient budget was investigated in a linear model using the *stats* package. The effect of BNF and livestock density were also analysed for each region separately using a linear model and the *stats* package. The influence of nutrient input, BNF, livestock density, and study region on the farm output was also assessed in a linear model using the *stats* package. Post-hoc test to determine differences among study regions were performed using Tukey’s HSD test for unbalanced data sets with the *agricolae* package. Correlation between BNF and livestock density was analysed in a linear mixed model with study region as a random factor with the *lmer* package. Assumptions of normality and homogeneity were checked by visual assessment of the residual versus fitted plot and normal *Q*–*Q* plot. To analyse any correlation between source of input (in percentage of totalnutrient input) and total nutrient input, livestock density, years under organic management, cultivated farm area, and percentage of BNF a correlation matrix and correlation plot were done using the *corrplot* package.

Results

Nutrient balances

Across all 71 studied farms, results yielded an average surplus of N, a small surplus of potassium (K), and a small deficit of phosphorus (P) (Table 2). The variability among regions and farms was high, especially for N and K (Fig. 1). For N balances, the average was positive 28 (standard deviation = 42) kg N ha^{-1} year^{-1}, although 17 of the 71 farms had negative N balances.

The highest N surpluses were detected in Switzerland, followed by Denmark and Germany North, while the lowest surplus was found in Germany South. Yet, there were no significant differences observed between countries.

Further, over all 71 farms, farms with a higher livestock density seemed to have higher N balances compared to stockless or farms with a low livestock density (Table 2). However, due to high variability with the data this effect was not significant ($F_1 = 2.24$, $p = 0.140$). Since a large proportion of N inputs derived from BNF, for which estimation can hold high amounts of uncertainties, N balances were also calculated for a 10% and 30% higher and lower BNF. On average the N balances changed by approximately 4 and 12 kg N ha^{-1} respectively due to the change in BNF (Supplementary Table 2).

In contrast to N, the majority of P and K farm gate balances revealed deficits, with 66% and 56% of the balances being negative, respectively (Fig. 1). Across all cases, the P balances averaged −1 kg P ha^{-1} year^{-1} and were primarily in the range of 0 to − 10 kg P ha^{-1} year^{-1}, whilst K was slightly positive at 2 kg K ha^{-1} year^{-1}, although with large variation. The highest P surplus was found in Denmark, followed by Italy, and the biggest deficits in Germany South and Hungary. However, the only significant differences were found between Denmark on the one hand and Germany South and Hungary on the other hand ($F_{(7)} = 2.33$, $p = 0.035$). Inventoried farms in five of the eight

Table 2 Mean values and standard deviations for nutrient balances for N, P and K (in kg ha^{-1} year^{-1}) and for proportion of nitrogen inflow from biological nitrogen fixation (BNF in %)

Region	Farm type	No. offarms	N Kg ha^{-1}	P	K	BNF (%)
Denmark	High stocked (> 1.0)	1	29±0	68.8±0	18.3±0	31.3±0
	Low stocked (0.1 < x < 1.0)	3	22.8±20.3	0.2±4.1	9.7±8.9	50.4±16.9
	Stockless (< 0.1)	3	49.7±79.7	5.3±10.2	42.1±52.3	15.8±13.7
	Average	7	35.2±49.4	12.2±25.9	24.8±34.8	32.9±21.4
Estonia	Low stocked (0.1 < *x* < 1.0)	5	22.8±16.3	−1.7±1.1	−1.7±1.4	96.2±3.8
	Stockless (< 0.1)	6	26.2±11.4	−3.6±1.2	−3.9±4.1	98.5±3
	Average	11	24.6±13.2	−2.7±1.5	−2.9±3.2	97.5±3.4
Germany North	Low stocked (0.1 < *x* < 1.0)	3	52.8±57.4	−6.9±2.8	−11.3±13.2	41.3±49.4
	Stockless (< 0.1)	7	21.2±40.8	1.3±8	22.8±32.2	37.2±25.1
	Average	10	30.7±45.5	−1.2±7.7	12.6±31.6	38.4±31.1
Germany South	Low stocked (0.1 < x < 1.0)	4	17±15.4	−3±4.5	−3.6±10.3	84.8±19.5
	Stockless (< 0.1)	6	0.2±21.2	−4.4±4.3	−1.1±29.9	59.9±27.4
	Average	10	6.9±20.1	−3.9±4.2	−2.1±23.1	69.9±26.6
Hungary	High stocked (> 1.0)	2	−18.7±74	−12.3±1.9	−51.8±2.5	99.9±0
	Stockless (< 0.1)	8	24.9±48.8	−0.7±6.9	9.1±30.3	47.7±37.8
	Average	10	16.2±52.9	−3±7.8	−3.1±37.1	58.1±39.9
Italy	Stockless (< 0.1)	5	16.1±51.9	9.1±21.1	0.7±92.7	60.4±50.1
	Average	5	16.1±51.9	9.1±21.1	0.7±92.7	60.4±50.1
Switzerland	High stocked (> 1.0)	4	62±24.3	0±3.9	−1.9±33.9	53.5±29.8
	Low stocked (0.1 < *x* < 1.0)	3	56.3±33.7	1.3±3.7	−2±7.3	39.2±7.6
	Stockless (< 0.1)	3	53.1±28.6	−0.7±4.4	−0.1±16.1	43.9±12.7
	Average	10	57.6±25.4	0.2±3.6	−1.4±21.3	46.3±19.7
United Kingdom	High stocked (> 1.0)	5	38.3±76	−3.7±9.4	−4.4±15.8	86.4±18.9
	Low stocked (0.1 < *x* < 1.0)	3	−2.9±34.9	−1.6±2.1	1.6±7.2	64±47.1
	Average	8	22.9±64.1	−2.9±7.3	−2.2±13	78±31.2
Average	High stocked (> 1.0)	12	35.9±59.6	2.1±22.3	−9.6±28.9	73.1±29.7
	Low stocked (0.1 < *x* < 1.0)	21	27.1±32.9	−2±3.7	−1.4±9.4	66.9±33.1
	Stockless (< 0.1)	38	23.5±41.2	0.4±9.8	8.7±41.7	54.1±34.3
	Average	71	26.7±42.3	0±11.6	2.6±33.6	61.4±33.6

Results are shown by country and farm type. Farm type is determined by livestock unit (LU) per ha (stockless < 0.1 LU ha^{-1}, low stocked = 0.1 LU ha^{-1} < x < 1.0 LU ha^{-1}, high stocked > 1.0 LU ha^{-1})

case regions had an average deficit for P. For K, three country averages showed surpluses (Denmark, Germany North, and Italy), while the highest deficits were found in Estonia and Hungary. Like the N balances, the average P and the K balances were not significant influenced by density (Estimate = 5.89 kg P ha^{-1} per LU ha^{-1}, $F_{(1)} = 3.23$, $p = 0.077$, and Estimate = −6.8 kg K ha^{-1} per LU ha^{-1}, $F_{(1)} = 1.16$, $p = 0.286$, respectively). Yet in contrast to the N balances, the P and K balances decreased with increasing reliance on BNF (Estimate = −0.16 kg P ha^{-1} per %BNF, $F_{(1)} = 16.56$, $p < 0.001$, and Estimate = −0.46 kg K ha^{-1} per %BNF, $F_{(1)} = 14.85$, $p < 0.001$, respectively).

The role of biological nitrogen fixation and farm type

The average proportion of external N inflows derived from BNF was 61%, with an average absolute amount of 36 kg N ha^{-1}, ranging between 24 and 61 kg N ha^{-1} (Supplementary Tables 3 and 4). On average, BNF was 104 kg N per ha legume cropped. Supplementary Table 3 gives more detailed information about the area under legumes

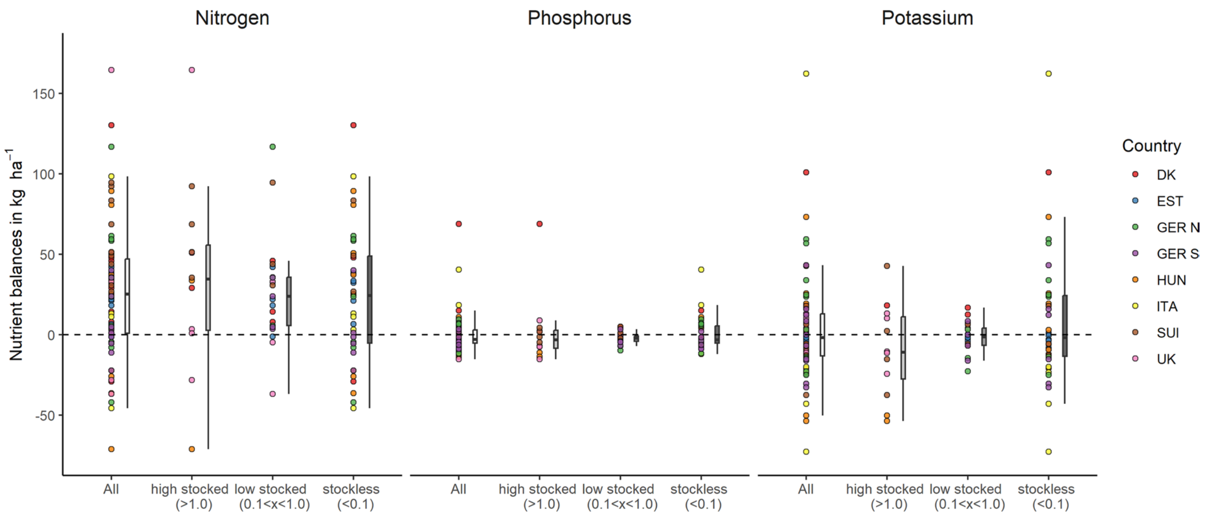

Fig. 1 Boxplot of three-year averaged values for nitrogen, phosphorus, and potassium farms scale nutrient balances grouped by farm type for all 71 farms across all sites. Each dots represent one farm; colours represent the study region

and the rate BNF. A large difference between regions was observed—Estonian farms relied on average over 95% on BNF for their N supply, inventoried farms in Denmark had only a reliance of just below 30% on average. The reliance on BNF as an N source increased overall with livestock density (Estimate = 11.1% BNF per LU ha^{-1}, $F_{(1,69)} = 3.99$, $p = 0.0497$).

N input derived from BNF had a non-significant negative correlation with the N balances (Estimate = – 0.21 kg N ha^{-1} per BNF%, $F_1 = 2.14$, $p = 0.149$), but a significant negative correlation with P balances (Estimate = – 0.16 kg P ha^{-1} per BNF%, $F_1 = 16.57$, $p < 0.001$) and K balances (Estimate = – 0.46 kg K ha^{-1} per BNF%, $F_1 = 14.85$, $p < 0.001$). A significant positive correlation was found between the absolute amount of N from BNF and the N balance (Estimate = 1.02 kg N ha^{-1} per kg N ha^{-1}, $F_1 = 51.33$, $p < 0.001$), highlighting the importance of BNF for organic farms. Due to high variance, no correlations were found between livestock density and N (Estimate = 8.9 kg N ha^{-1} per LU ha^{-1}, $F_1 = 2.24$, $p = 0.140$), P (Estimate = 5.8 kg P ha^{-1} per LU ha^{-1}, $F_1 = 3.23$, $p = 0.077$), and K (Estimate = – 6.8 kg K ha^{-1} per LU ha^{-1}, $F_1 = 1.16$, $p = 0.0.286$) balances.

External nutrient inputs

Averaged across all 71 farms, annual amounts of external nutrient inputs were 44 kg N ha^{-1} (excluding BNF), 10 kg P ha^{-1}, and 31 kg K ha^{-1} (Fig. 2), but the reliance on external inputs (and the importance of BNF) varied across the eight regions and three farm types. For example, Estonia, UK, Germany South, and Hungary sourced less than 20 kg N ha^{-1} externally, which was less than the N contribution by BNF. Estonia, Hungary, Germany South, and the UK had much lower external P and K inputs than Denmark, Italy, Switzerland, and Germany North. Further, the amount of external nutrients sourced was higher in farms with lower livestock density or stockless farms, than in farms with a high livestock density.

The average proportion of external nutrients sourced from conventional origin, which includes animal manures as well as digestates from conventional farms, was 16% for N, 18% for P and 23% for K (Fig. 2). This indicates a generally low utilization of conventional manure sources, although it is important to consider the differences across sites. High reliance on conventional manures was found in Denmark, Estonia, Hungary, and Germany South, while it was low in the United Kingdom and Germany North.

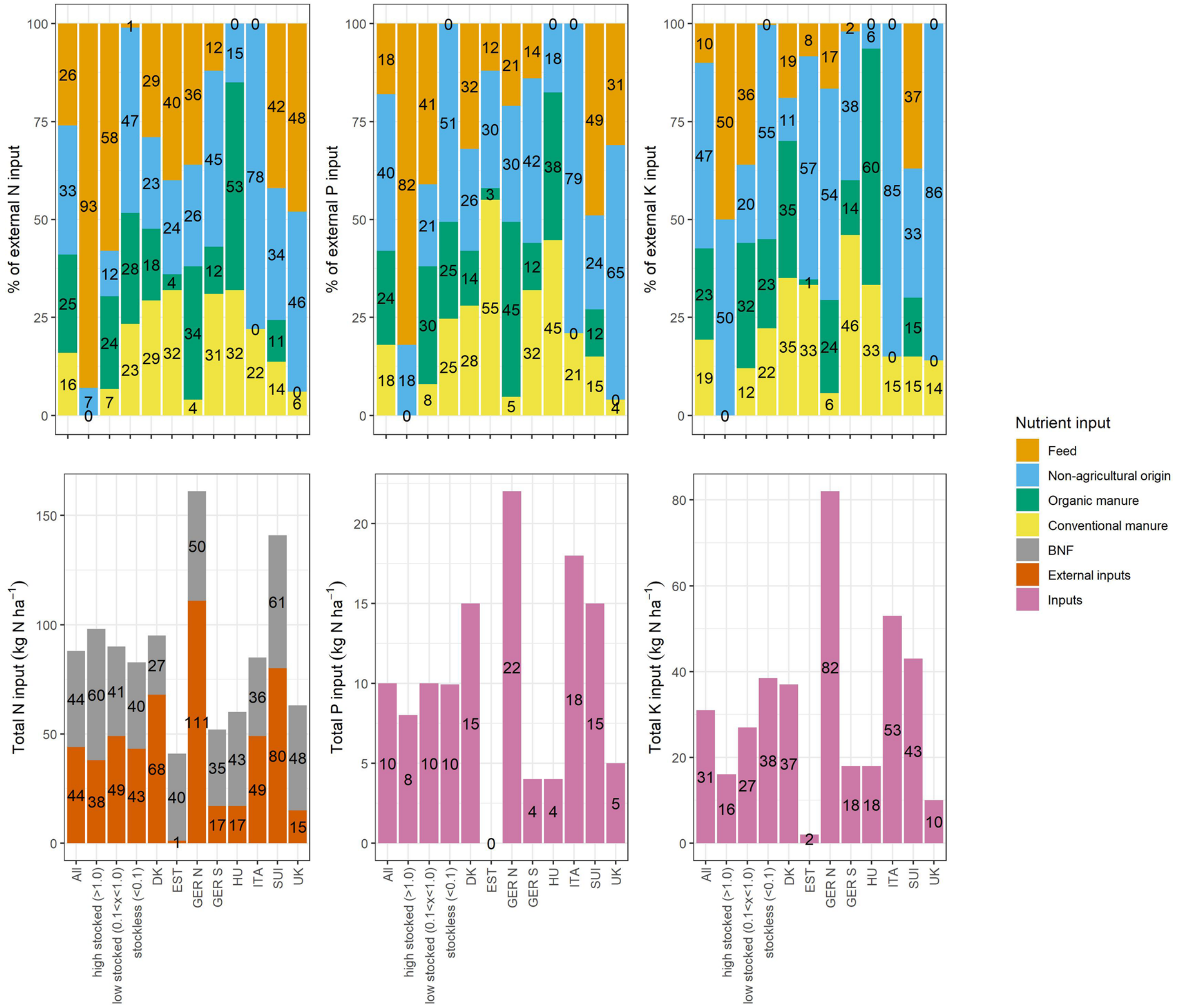

Fig. 2 Nitrogen (N), phosphorus (P) and potassium (K) inputs on organic farms, showing relative distribution of external input types utilized (upper figure) and absolute, aggregated total nutrient inputs (divided in external inputs and biological fixated N (BNF); lower figure). Stocking density is determined by livestock unit (LU) per ha (stockless < 0.1 LU ha^{-1}, low stocked $= 0.1$ LU ha$^{-1} < x < 1.0$ LU ha^{-1}, high stocked > 1.0 LU ha^{-1}). Fertilizers considered as of non-agricultural origin are among others: digestates and composts from urban waste, recycled fertilizers from food industry waste (for example vinasse from sugar beet production), and commercial fertilizers. (DK = Denmark, EST = Estonia, HU = Hungary, UK = United Kingdom, ITA = Italy, SUI = Switzerland, GER N = Northern Germany, GER S = Southern Germany)

Sources of conventional manure (across countries) included cattle (manure or slurry), pig slurry, mink slurry, horse manure, and digestates from conventional biogas plants (Supplementary Table 4). Italy, UK, and Estonia had no, or very little externally sourced organic manures utilized on farms, whilst Hungary and Germany North had the highest proportions of nutrients from organic manure sources. Chicken and cattle manure followed by digestates from organic biogas plants were the most common sources of organic manure. Feed inputs constituted an important aggregate external nutrient input for all sites, although around half of the farms were stockless and did not source any feed.

The non-agricultural origin category (organic inputs other than from direct agricultural provenience) was an important source of external input across all countries. The average proportion of non-agricultural inputs for N, P and K, across all farms, was higher than that of conventional manures. The main types in this category were composted municipal waste, digestate from communal biogas plants (Supplementary Table 4), as well as commercially sold fertilizers. The latter were usually in a pelletised or liquid form and derived from various organic materials. These commercial fertilizers were especially utilized in Italy and on farms with high revenue crops like vegetables. In Germany North spent mushroom substrate was also an important nutrient source in this category. Inputs from non-agricultural origin were a particularly important input source for N, P and K for the UK, Italy, and Germany South (Fig. 2). Although external nutrient inputs for UK were low, the proportion of non-agricultural inputs was high, particularly for P and K.

For the farms in GER N, GER S, and SUI, imported nutrients by seeds were also recorded. These imports, however, contributed only small amounts of nutrients on the overall scale with a median nutrient import of 1.9 kg N ha^{-1}, 0.31 kg P ha^{-1}, and 0.53 kg K ha^{-1}.

Farms with a high livestock density (>1 LU ha^{-1}) relied on feed as their main external nutrient source, especially for N (93% of external nutrient inputs, Fig. 2), while P and K were also sourced from non-agricultural origins. The amount of external manures (conventional or organic) and to some extend the amount of inputs non-agricultural sources were lower when the stocking density increased. This is also shown by the performed correlation matrix over all regions among the different sources of inputs (as percentage of total nutrient input), total nutrient input, stocking density, cultivated farm area, years under organic management, and reliance on BNF. There were few significant correlations ($p<0.05$, Supplementary Figure 2). The amount of nutrient derived from BNF, and the total nutrient inputs had negative correlation (coefficient between -0.62 and -0.69). Further, an increase in BNF also resulted in fewer organic manures were sourced. Farms with higher livestock densities, imported higher amounts of nutrients from feed (coefficients 0.35–0.44). Farms that relied to a higher percentage on feed imports also showed lower nutrient sourced from organic manures and non-agricultural sources. The area a farm cultivates does not correlate to a specific nutrient source. Farms which imported more nutrients also showed a higher import of organic manures. Yet, this might be due to the very high nutrient inputs of farm GER N_02, which import very high amount of nutrients from an affiliated organically run biogas plant.

Eleven of the 71 farms included in this study did not utilize any external inputs (Supplementary Table 4). Five out of theses farms were in Estonia, three in Germany South, and two in the UK, and one in Germany North. Six of the farms without external inputs were stockless, while 5 of them had medium or high livestock densities. P and K balances were significantly higher for farms using external inputs (0.1 kg P ha^{-1} year^{-1} vs. -6 kg P ha^{-1} year^{-1} ($p<0.05$)); and (4 kg K ha^{-1} year^{-1} vs. -10 kg K ha^{-1} year^{-1} ($p<0.01$)). N balances were higher for farms using external inputs (30 kg N ha^{-1} year^{-1} vs. 7 kg N ha^{-1} year^{-1}), but not significant ($p=0.08$).

There are also differences between countries that hint to the availability of external inputs and infrastructure of the regions when comparing the kind of inputs utilized on farms and the distances they have been transported (supplementary. While in Denmark, Germany North and South, UK, and Switzerland there are several inputs used per farms and often come from neighbouring farms or close by recycling plants, in Italy, Hungary and Estonia commercial products and pelletised manures traded across Europe are often used. Further, the number of different inputs per farm is lower for the latterly named regions.

Farm nutrient outputs and productivity

Farm nutrient outputs (Fig. 3) provide a high-level overview of the production output per land unit of the systems assessed. The average nutrient outputs were 55 kg N ha^{-1}, 10 kg P ha^{-1} and 28 kg K ha^{-1}. The N output per area of stockless farms and highly stocked farms were similar and averaged at 58 and 60 kg N ha^{-1}, respectively. Low stocked farms showed a lower N output per land unit with 48 kg N ha^{-1}. Yet, stocking density as well as reliance on BNF and study region were not significant influences on N output ($F_{(1)}=0.24$, $p=0.629$, $F_{(1)}=3.76$, $p=0.057$, and $F_{(7)}=1.88$, $p=0.089$, respectively). But the N output was significantly influenced by the N input (Fig. 3, Estimate = 0.39 kg N ha^{-1} per kg N ha^{-1}, $F_{(1)}=102.92$, $p<0.001$). Figure 3 presents an input output assessment for N to provide an indication

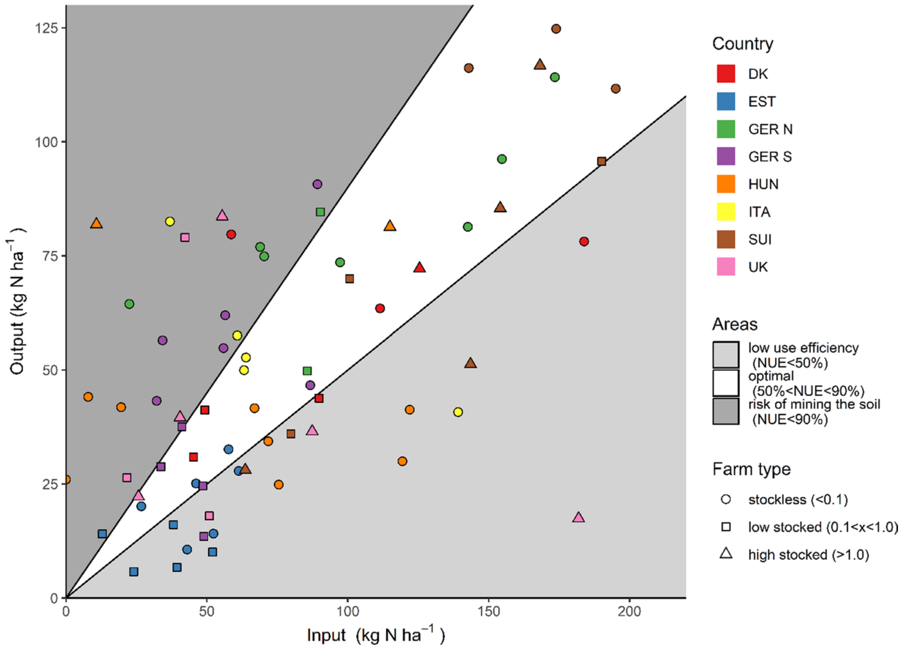

Fig. 3 Nitrogen input–output graphs for 71 organic farms included in the study. Inputs and outputs are given in kg ha^{-1} year^{-1}. The upper line represents a 90% nitrogen use efficiency (NUE) and the lower line a 50% NUE. Farms are divided by farm type according to livestock density measured in livestock unit (LU) per ha (stockless = 0 LU ha^{-1}, low stocked < 0.1 LU ha^{-1}, medium stocked = 0.1 LU ha^{-1} < x < 1.0 LU ha^{-1}, high stocked > 1.0 LU ha^{-1})

of the N use efficiency (NUE) and production output per land unit of the organic farms. This way of analysing the production and productivity of farming systems was suggested by EU Nitrogen Expert Panel (2015). They defined a NUE between 50 and 90% as optimal (white area Fig. 3), while higher NUE were defined at risking soil depletion (dark grey area Fig. 3) and lower NUE as inefficient (light grey area Fig. 3). Many farms had a low NUE (below 50%). Although there are observable differences between countries, for example Germany North, Switzerland, and Denmark are mostly above the 50% line, whilst Estonia is mostly below, and Hungary and Italy vary across the spectrum. The data also shows that 38% of farms are within the optimal band, while respectively 31% of farms had a NUE level below (< 50%) and above (> 90%) the range optimal.

Factors driving variability among farms

High variability between farms could be observed in the sections above. To look into the factors driving the variability and to reveal any groupings among farms, a principal component analysis of the farm data including nutrient (N, P, K) inputs and outputs, percentage of nutrients derived from nutrient source averaged for N, P, and K, livestock density, reliance on BNF, years under organic management, share of crops in the rotation, and cultivated area was performed. The first PC could explain 24% of the variation between farms, while PC2 explained 13%, PC3-8 explained between 10 and 7%, and PC9 and onwards explained less than 5% (Supplementary Figure 3).

The biplot of the first and second PC does not reveal a clear grouping of farms (Fig. 4). However, if they are grouped by farm type, PC2 differentiates more between farm types than PC1. Yet, there is a relevant overlap at the coordinate cross. Stockless farms are especially contributed horizontally over PC1 while rather unaffected by PC2. Highly stocked farms are more spread out over PC2. The loading scores for PC can show some explanation. PC1 is mainly driven by the amount of nutrient inputs negatively, and the reliance of BNF positively, while PC2 is driven negatively driven by livestock density, share of pasture in the rotation, and the percentage of recycled nutrients, and the percentage of feed imports (Fig. 4, Supplementary Table 5).

Grouping the farms by study regions rather than by farm type does also not result in a clear grouping (Supplementary Figure 4). However, there is high overlap between DK, SUI, and GER N on the one hand, and EST, UK, and GER S on the other hand. ITA and HU overlapped as well and follow the distribution of the stockless farms.

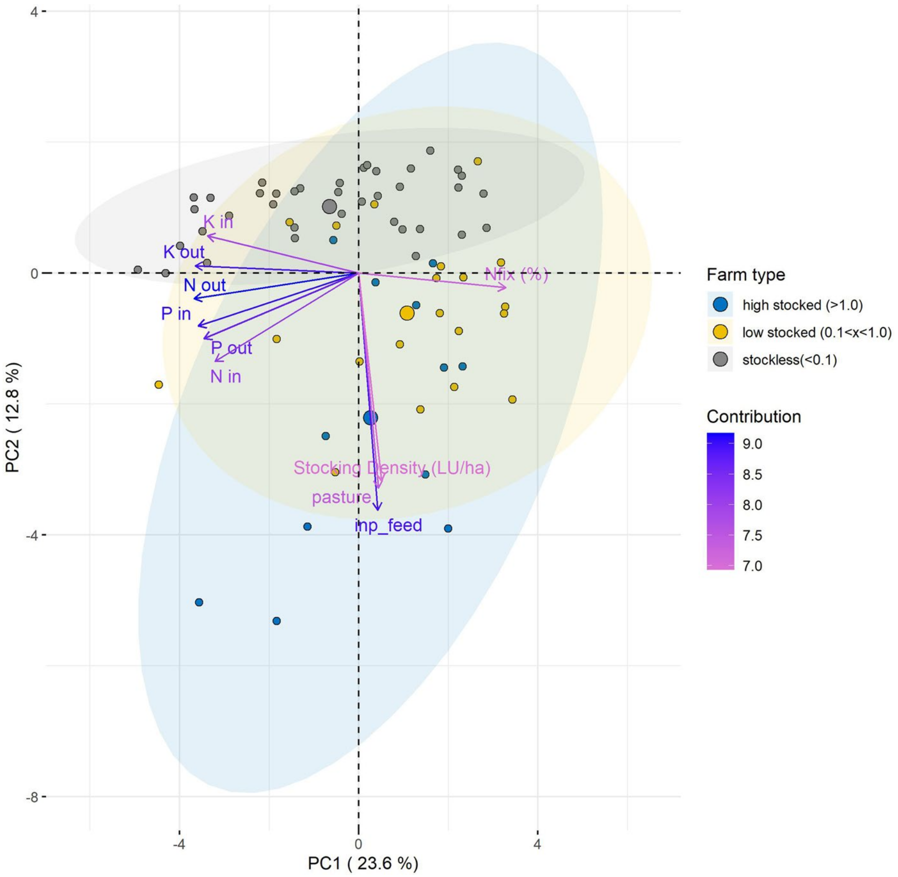

Fig. 4 Principle component analysis (PCA) biplot of the farm data including nutrient budgets, nutrient inputs and outputs, percentage of nutrients derived from nutrient sources for N, P, and K, livestock density, reliance on biological N fixation, years under organic management, percentage of area under certain crop species groups, and cultivated area. The biplot shows the relationship between the first two principal components (PC1 and PC2) and the amount of variation explained by each PC is given as well in parentheses on the axes. The dots represent each farm and the colour and corresponding coloured ellipse, and larger estimated mean point show the farm type. The blue to purple arrows represent the 10 variables with the highest scores. The colour scale of each arrow indicates the strength of the variable's contribution to the principal component, and the angle between the arrows represents the correlation between the variables (N/P/K in = total farm N/P/K input, N/P/K out = total farm N/P/K output, inp_feed = % of inputs derived from feed imports (mean over NPK), pasture = % of pasture in crop rotation)

Farmer's acceptability of external input types

When not specifying fertilizer type, the general acceptance of recycled fertilizers (fertilizers derived from industry and urban wastes) was high with 80% of all farmers willing to use recycled fertilizers on their farm. When asked about specific types of recycled inputs, the highest acceptance, across all farmers, was for green waste (e.g., cuttings and prunings). Animal products (blood, horn, or bone meal), digestates and composted household waste were accepted by 60%, 50% and 50%, respectively. A very low acceptance was found for sewage sludge and sewage sludge products (Supplementary Figure 5). However, it needs to be noted that fertilizers derived from human faecal matter are not permitted for use in European organic farming systems inputs (European Commission 2018). The acceptability of recycled fertilizers differed between countries. For example, the acceptance of sewage sludge was much higher in Denmark and the UK compared to the other countries. When probed regarding why input types were acceptable or not acceptable, positive aspects mentioned were the closing of nutrient cycles and the addition of organic matter to the soil. The most common concern (e.g., 50% for sewage sludge, 28% for sewage sludge products, and 31% for household waste compost) raised was that the products might be contaminated, primarily potentially toxic elements and organic pollutants. For household waste derived composts, the contamination with plastic was also of high concern (29% of farmers). For the sewage sludge and sewage sludge products, a distinctive concern expressed was one of societal acceptance (13%, and 8%, respectively).

Discussion

Nutrient imbalances

The results on the broad range of balances indicated that current fertility management poses a risk either for harming soil fertility, primarily by depletion of P and K, or to harm the environment due to strong N and P surpluses. The sum of these findings indicates that especially farms with a high reliance on BNF experience a deficit of P and K. A correlation between farm type and nutrient budget was not shown in the data set due to the high variation within the farm types. This variation could be caused by the availability of external fertilizers for each farm and/or personal ideology about nutrient management of the farmer itself. Yet, if farms use little to no fertilizer inputs, the nutrient deficiency is seen stronger in stockless farms than in farms with livestock. For the N balances, other studies found a similar pattern of organic farms having surpluses, some of them with a higher proportion of farms with positive balances (Watson et al. 2002). Berry et al. (2003) and others with a higher range of farms with negative N balances (Foissy et al. 2013). However, it should be considered that the N balances are related to a higher degree of uncertainty than the P and K balances, as the assessment of the inputs via BNF is related to several assumptions with a high degree of variation, and N is lost more easily (Watson et al. 2006).

Nitrogen losses occur in different places in an agricultural system. The main loss pathways are nitrate leaching, ammonia volatilization, denitrification, and nitrous oxide emissions from denitrification and nitrification (Cameron et al. 2013; Manu et al. 2021). Taube and Pötsch (2001) estimated that 30% of N losses from animal manure application with an organic farming system are unavoidable during application and storage. On average 42% of external inputs which is equal to 18 kg N ha^{-1} were derived from organic or conventional animal manures or digestates, in the current study. Considering these losses, the N budgets would on average be reduced from 28 to 23 kg N ha^{-1}. However, it needs to be considered that this just concerns the external inputs and not the unavoidable losses from internal animal manures. Nitrogen losses due to nitrate leaching are the main N losses in agricultural system, yet the amount leached is mainly dependent on soil type, climate (especially precipitation), crop rotation (e.g., catch crop cultivation), and N application rate (Pandey et al. 2018; Wang and Li 2019). Pandey et al. (2018) measured N leaching in a range of 4–88 kg N ha^{-1} depending on soil type climate within Denmark. Biernat et al. (2020) measured nitrate leaching under low N intensive and semi-N-intensive organic farming systems in Northern Germany to be 22.0 and 24.4 kg N ha^{-1} respectively. However, the method of farm gate nutrient balances, which was used in this study does not considering these N losses or inputs such as atmospheric deposition (Watson et al. 2002). Farm gate nutrient balances are partial balances that are just looking at the flows going in and out of the farm. Therefore, farm gate nutrient balances might not reflect the actual nutrient plant supply on field level. This is also shown by the increase farm production due to higher N inputs, even though the farms had already positive N farm gate balances (Fig. 3).

Agricultural systems should have moderately positive N balances to compensate for uncontrollable losses and—at least on a long-term perspective—balanced P and K input–output-flows to secure sufficient nutrient supply. A lower N supply will have negative effect on yields, as indicated in the present study by the correlation between N supply and N output. This is in line with several indications from the literature that N is the main factor limiting yields after conversion to organic farming (Berry et al. 2003; Döring and Neuhoff 2021; Wilbois and Schmidt 2019). Furthermore, the data indicates that potentially the land use related to BNF provided a relative drag on farm production (outputs), as would be expected if the main contribution was to provide green manure to supply N to the farming system. Large shares of areas for green manure without further use are typical for stockless farms with high reliance on BNF. In livestock systems this green manure can be better utilised for fodder and thus produces a from output in terms of animal products and manure. This leads to higher production of livestock farms if both farms use low amount of external inputs. However, our data has shown that stockless farms with adequate amounts of inputs have a higher production than livestock farms due to a lower efficiency of nutrient conversion in animals compared to plants.

The extent of deficits across all case areas, especially for P, is cause for concern regarding the sustainability of some organic systems. This is in line with other studies. Watson et al. (2002) found deficits for P in mixed and arable systems, while K was negative in mixed systems and positive in arable systems. Gosling and Shepherd (2005) indicated that arable organic farms are mining reserves of P and K built up under conventional management. In a long-term perspective, any farming system must ensure an equilibrium of inputs and outputs to secure the long-term sustainability in terms of soil fertility. The nutrient balances for P and K are strongly influenced by the reliance of the farming system on N inputs from BNF and the use of external inputs, where farms with a deficit either did not source external inputs or utilized insufficient volumes or not well-balanced sources related to system offtakes.

Where N demand is largely met by BNF, slight deficits in P and K balances may take many years to translate into a yield penalty, and unlike for N, this is a creeping process. Therefore, this strategy also needs to be accompanied by inputs of P and K.

It is becoming more and more established that achieving a balanced P supply is a significant challenge for soil fertility management on organic farms (Nowak et al. 2013; Cooper et al. 2018; Möller 2018). The data presented in this study shows a more complex picture. In Estonia, for example, where all farms had P deficits, the extent and volume of use of external inputs was limited. In contrast to this, external inputs were more common in Denmark and the volumes applied were considerably higher, meaning that more farms had a surplus of P. This indicates an unbalanced utilization of suitable P fertilizers throughout Europe, either by P undersupply in farming systems with low external inputs, or P oversupply in farming systems with large external inputs such as composts or animal manures, as previously shown by Tittarelli et al. (2017), Zikeli et al. (2017) and Möller (2018). Countries with a more recent history of organic farming and less intensive systems seem to face the challenge of low nutrient availability, while countries with more intensive systems rely more strongly on external inputs and are facing the challenge to replace contentious inputs by more adequate sources. Another opportunity for organic farms, besides sourcing more P fertilizers, is to improve crop P uptake and use-efficiency, as outlined by Cooper et al. (2018) and Möller et al. (2018)). However, this strategy is only a transitional approach, on a long-term perspective a balance of inputs and outputs is mandatory to avoid a decrease of soil fertility and productivity.

External nutrient supply

The data provide an indication that the extent of ‘reliance’ on conventional sources, on aggregate, is 16–19% for N, P and K. Whilst this can be considered moderate, the proportion is important considering the nutrient deficits observed and the significance of a potential move to restrict the use of such input types. A limited amount of work has been undertaken assessing use of external nutrients inputs, primarily by Nowak et al. (2013) who found (in arable systems) average inflows from conventional farms of 23%, 73% and 53% for N, P and K, respectively. Foissy et al. (2013) found a large reliance on purchase of organic manures by stockless farmers in France. In general, however, our data also indicate that diverse sourcing strategies are utilised, with nutrients being sourced from a variety of types, often what is regionally available, defendable in terms of organic practices and economically sustainable.

Sourcing nutrients is however different depending on farm type. Farms with livestock have the possibility to recycle nutrients on farm through their livestock. Access to feed imports and BNF covers their nutrient demand. Yet, the sourcing of organically produced feed does not represent a net import of nutrients into the organic farming system, but rather a redistribution of nutrients from stockless feed producing farms to livestock farms. This enhances the need of nutrient sources tailored to organic stockless farms that are derived of sources outside the organic farming system such as recycled fertilizers from urban wastes.

The inventories indicate that BNF is in most countries still the main N source in organic farming systems, as previously reported in literature. In France, BNF contributed 63% of the N inflows (Nowak et al. 2013) and Foissy et al. (2013) report a contribution of 44%. In the UK, Berry et al. (2006) found a range of 35–46% for stocked systems and an average of 70% for stockless systems. Farms with a high reliance on BNF as a main N source are more strongly affected by balance deficits of P and K, which may have negative feedback effects on BNF at least on a long-term perspective (Reimer et al. 2020a; Römer and Lehne 2004), highlighting a dilemma for the organic sector.

Farmland use-efficiency and productivity

Farm production per land unit, which is also often defend as land use-efficiency, can be measured as the total N output per land unit of a farm (Quemeda et al. 2020). The nutrient output data presented indicate that the organic systems, on aggregate have a low output, with an average N output of 55 kg N ha^{-1} (median value is 44 kg N ha^{-1}) compared to the N output level of conventional farms (approximately 100 kg N ha^{-1};Quemada et al. 2020). The yields in organic farming system have been reported to be globally 75–81% of the ones of conventional farming system (Meemken and Qaim 2018). Yet, the yield gap increases in countries with a general high productivity (e.g., northern Europe 70%) and if measured by on-farm statistics (76%) (de Ponti et al. 2012). However, these studies are usually crop based and do not take into account differences in crop rotation design between organic and conventional farming. The integration of non-productive green manures further increase the yield gap (de Ponti et al. 2012). Yet, Barbieiri et al. (2019) only found a reduction of global protein production of 23.1% in a 100% organically managed agricultural system, not taken into account the higher yield gap in areas with high yield potential. Similar results have been found by Ponisio et al. (2015) who found only a 19% yield gap due to diversification within the organic sector. Assuming a conventional yield of approximately 100 kg N ha^{-1} (Quemeda et al. 2020) the reduced yield of organic farming system could be assumed to be to around 60–70 kg N ha^{-1}. Thus, the mean N output of this study reflects a rather low output of N for organic farming system. The low production intensity of farms within the sample of this study, especially present in Estonia and Hungary could be one reason. This is also reflected in the huge disparity in resource accessibility reflected in the type, source, and distances for provisioning of external nutrients (Supplementary Table 4). Limiting the data to more intensive agriculture evident in Denmark, Switzerland and Germany North, the average N output is 79 kg N ha^{-1}, with a median of 74 kg N ha^{-1}. The productivity level in organic farming is driven by the external inputs and N inputs via BNF. Quemada et al. (2020) reported average N outputs of 105 kg N ha^{-1} for arable farms, 81 kg N ha^{-1} for mixed dairy and 153 kg N ha^{-1} for mixed pig farms across Europe. Considering that yield levels in organic agriculture are often assumed to be around 75% of the level found in conventional agriculture, the yields found in Denmark, Switzerland and Germany North are generally in line with the findings of Quemada et al (2020), while the N outputs in other countries are lower. Thus, farms relying less on external inputs, and more on BNF generally have a lower output of N, and thus a lower land-use efficiency. Yet, besides N output the calory output by a farming system can also be a good indicator of land-use efficiency and further studies on the effect of increased N supply on the calory output of organic systems are needed.

In countries with more intensively managed agriculture, higher yields need to be achieved to be able to farm at an economic surplus (high land prices). Therefore, the targeted yield levels might be different. In the process of intensification, substitution of inputs from BNF to external inputs thus inevitably occurs. In addition, other factors such as water can limit yields (for example in Italy or Hungary), hence higher N supply might increase the N balance without resulting in higher yields. In countries with more favourable growing conditions (for example Germany or Denmark), additional N supply can lead to higher yields, without directly causing higher N surpluses (Doltra et al. 2011).

Conclusions

Nutrient management in organic farming moves in a very narrow range between inputs via BNF, the unproductive gaseous and leaching N losses, and balancing out of P and K exports via inputs of external nutrient sources. The nutrient supply of a farm is determined by its farm type, reliance on biological N fixation, and access to external nutrients, which are in turn influenced by the farm's location. Livestock farms can cover their nutrient demand by feed imports while stockless farms are dependent on external fertilizer inputs. Therefore, if access to external nutrient supply would diminish because of future regulations (for example of 'contentious inputs') as well as anticipated increased demand, then the outputs from the more intensively managed stockless farms would be expected to decrease. Consequently, access to nutrients outside of the organic farming system, preferably from recycled sources, are needed to ensure the sustainability of nutrient management in organic farming.

There are two key points for future consideration regarding nutrient management in organic farms. The first is how to ensure the sustainability of a sufficient nutrient supply given an expected increase in the organic area across Europe. Whilst farms can theoretically source more N from BNF, increasing the organic land base as planned will either require that more land be dedicated to legumes to secure a sufficient N supply (and consumer demand increases) or through the provision of more external inputs. The use of external P and K inputs that contain relevant amounts of N can boost the overall productivity of the system, and the use of fertilizer treatment technologies that are able to keep the N in the productive process are of crucial importance in organic farming. Intricately linked to this, the second point relates to considerations of the types and availability of external inputs which organic agriculture would deem acceptable in future to fulfil the nutrient needs, particularly the use of conventional manures.

It is notable that the concept of 'contentious inputs' in organic farming is debated and a lack of clarity remains about how to define what is contentious in relation to soil fertility maintenance. In future, organic agriculture will need to clarify its position regarding the definition of "contentious" inputs to clearly guide decisions regarding their utilization. The more restricted the definition, the lower the degrees of freedom for designing balanced systems, meaning not only N, but also the other macro nutrients. In this context, sustainable expansion of the organic sector will require an assessment of the volumes and types of organic wastes locally available for use, as well as its position regarding the sources of such wastes (e.g., sewage sludge). If the new target set for organic farming by the European Commission in the Farm to Fork strategy is to be realized, it is not trivial to strive for a higher farm output, and an increasing land-use efficiency. This will develop in a time where climate change will stress the food systems, and where there is a general wish to increase and protect undisturbed natural areas.

Authors contribution All authors contributed to the study conception, design, and data collection. Material preparation, and analysis were performed by MO, MR, and SB. The first draft of the manuscript was written by MO and MR and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by Royal Danish Library, Aarhus University Library. This work has been done in the frame of the RELACS project which has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 773431. The RELACS project has been funded with support from the European Commission. This publication reflects the views only of the authors, and the European Commission cannot be held responsible for any use which may be made of the information contained therein.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Consent for publication The authors affirm that human research participants provided informed consent for publication of farm data.

Consent to participate Informed consent was obtained from all individual participants interviewed for the study as part of the Ethics procedure set out for the research project.

Data and code availability The datasets and R code generated during and/or analysed during the current study are available from the corresponding author on reasonable request. Supplementary material is available under the following link: https://osf.io/75usq/?view_only=8bccfb13ba5344e7aa15277fe1df170e.

Ethics approval The RELACS project, under which the current research was undertaken, went through an Ethics review process within the framework of the requirements set out by EU Horizon 2020. Procedures in line with Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 were set out and followed for the research undertaken.

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