



# Reliance on Biological Nitrogen Fixation Depletes Soil Phosphorus and Potassium Reserves

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**Abstract** Limited nutrient availability is one of the major challenges in organic farming. Little is known about nutrient budgets of organic farms, the underlying factors or effects on soil fertility. We therefore assessed farm gate nutrient budgets for nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and sulfur (S) of 20 organic farms in Germany and analyzed their soil nutri-ent status. In average, the budgets showed a surplus of N (19 kg ha<sup>-1</sup>), K (5 kg ha<sup>-1</sup>), S (12 kg ha<sup>-1</sup>), and Mg (7 kg ha<sup>-1</sup>), and a deficit of P (−3 kg ha<sup>-1</sup>). There was, however, high variability between farms (e.g. standard deviation up to ± 36 kg N ha<sup>-1</sup>), which was mainly explained by different degrees of reliance on biological N fixation (BNF) as N source. When farms obtained more than 60% of their N input through BNF, they had deficits of P (mean −8 kg P ha<sup>-1</sup>) and K (mean −18 kg K

ha<sup>-1</sup>). Nutrient status of most soils was within the advised corridor, but for P, K and Mg, 10–15% of fields were lower and 45–63% were higher than advised. Extractable soil nutrient contents did not correlate with the nutrient budgets, inputs or outputs. Only extractable soil P increased with increasing P inputs and outputs. Furthermore, a decrease in extractable soil P was detected with a prolonged history of organic farming, indicating a risk of soil P mining in organic farming systems. In conclusion, the study revealed nutrient imbalances in organic farming and pointed to P and K scarcity as a major challenge for organic farms with high reliance on BNF in the long term.

**Keywords** Nutrient management · Organic farming · Germany · Soil depletion · Nutrient inputs · Farm gate budgets

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## Introduction

Nutrient management in organic farming differs significantly from the conventional approach in that the main goal is implementation of closed nutrient cycles rather than using mineral fertilizer inputs. However, any farming activity with the aim of selling food and feed products is subjected to nutrient offtakes. While nitrogen (N) can be supplied through biological N<sub>2</sub> fixation (BNF), all other nutrients must be replenished through external inputs to substitute offtakes, at least in the long term, in order to not degrade the system. The original concept of soil fertility management of the organic farming pioneers included efficient recycling of nutrients within the farms by re-distribution and application of animal manures (Vogt 2000). These systems, therefore, rely on livestock as a nutrient source for arable cropping systems. Additionally, the original concept of organic farming included efficient recycling of nutrients from urban environments, thereby ensuring a return of nutrients back to primary agricultural production (Heckman 2006). But, as of now, only few fertilizers derived from urban environments are permitted.

In Europe, the import of external inputs such as fertilizers into organic farms is currently regulated by the Council Regulation (EC) No 834/2007 (European Commission 2007), which are interpreted and put into practice by the national governments. However, a new revised version (Regulation (EU) 2018/848) has been passed by the European Council and will take effect in January 2021 (European Commission 2018). The following inputs will be permitted by the new regulation: (1) inputs from organic production, (2) natural or naturally derived products, (3) low solubility mineral fertilizers (European Commission 2018). The use of sewage on organic farmland was rejected due to philosophical considerations in the biodynamic farmers organizations, and it was prohibited in the other organic sectors in the second half of the 20th century due to concerns regarding contamination with potentially toxic elements (Vogt 2000). In most countries of Europe, as well as globally, a separated collection of organic household wastes is not sufficiently organized. Nutrient cycles are therefore open in organic farming, showing a unidirectional flow of nutrients from farms to the cities, with only minor returns from cities to farms.

In organic farming, special emphasis lies on the supply of phosphorus (P) and potassium (K). Especially for P, fertilizer sources for efficient fertilization are limited, as available external P fertilizers such as phosphate rock do not show convincing P fertilizer value in most soils due to their low reactivity in soils with a pH value > 5.5–6.0 (Möller et al. 2018). Other nutrient sources such as manures from conventional agriculture are considered contentious due to contamination and a structural dependency of organic farming on practices permitted only in conventional agriculture. Therefore, some countries such as Denmark are discussing tighter restrictions on the use of such contentious inputs. Although an adequate nutrient supply in organic farming may become an even greater challenge in the future, currently a convincing concept that ensures an adequate supply of nutrients through the use of mined or recycled nutrients in organic farming is still missing. Further, no comprehensive dataset is available on which kinds of inputs are actually used in organic farming.

The lack of an adequate nutrient supply is one of the major constraints of yields in organic farming (Berry et al. 2002; Möller et al. 2006; Askegaard et al. 2011). Nitrogen supply is often the limiting macro-nutrient after conversion to organic agriculture (Röös et al. 2018). Nitrogen availability is dominated by short-term effects from pre-crops, green manures and organic fertilization, while the legacy effect of previous conventional management and former supply of organic amendments has only minor effects on plant N supply. In contrast, plant P and K supply are dominated by soil processes and soil reserves, and omission of regular application of fertilizers has only minor effects on crop growth and performance in the first years after conversion (Løes and Øgaard 2001). However, omission of P supply affects the soil P level (Cooper et al. 2018), and low soil P, soil K and sulfur (S) availability also limit the ability of legumes to fix atmospheric N<sub>2</sub> (Römer and Lehne 2004; Scherer 2008). As the availability of P, K and S are major drivers for the overall N inputs via biological N<sub>2</sub> fixation into organic farming systems, it is therefore important to ensure adequate supply of these nutrient to sustain the overall productivity of the system. Therefore, investigations on the farms' nutrient flows and status are crucial in order to assess the sustainability of the farm's nutrient management practices with regard to productivity and soil fertility.

Farm gate nutrient budgets are a valid tool for assessing nutrient flows and input–output budgets in organic as well as conventional farming (Watson et al. 2002b). Essentially, they show the inflows and offtakes of nutrients at farm-scale and detect deficiency or oversupply of nutrients. Balanced nutrient inflow and offtake should be the goal of every nutrient management strategy. Farm gate nutrient budgets can also be used to assess short-term productivity as well as long-term sustainability of the system when they are used in combination with soil analysis.

Recent literature reviews on nutrient budgets of organic farms in Europe revealed that there is a high variability between studies as well as strong imbalances between the different nutrients regarding their stoichiometry (Möller 2018; Reimer et al. 2020). For example, published nutrient budgets of organic farms in Europe range from  $-175 \text{ kg N ha}^{-1}$  (Fliessbach et al. 2000) to  $246 \text{ kg N ha}^{-1}$  (Boldrini et al. 2007) for N, from  $-12 \text{ kg P ha}^{-1}$  (Erhart et al. 2002) to  $48 \text{ kg P ha}^{-1}$  (Zikeli et al. 2017) for P and from  $-143 \text{ kg K ha}^{-1}$  (Zikeli et al. 2017) to  $156 \text{ kg K ha}^{-1}$  (Løes and Øgaard 2001) for K. Further, balances indicate a strong surplus of some nutrients (e.g. P and S), and simultaneously a strong deficit of others (e.g. K) (Zikeli et al. 2017; Möller 2018). The nutrient deficits are usually more pronounced in stockless or sparsely stocked farms than in dairy farms due to higher nutrient outputs and lower potential of internal recycling through manure (Watson et al. 2002a; Ohm et al. 2017; Reimer et al. 2020). There is, however, still a knowledge gap on other factors besides farm type and differences in budgeting methods causing the variability in results across farms (Loges et al. 2006; Reimer et al. 2020). One often proposed factor is the stocking density (Giustini et al. 2008; Foissy et al. 2013). Other possible factors could be the origin of the nutrients (e.g. Zikeli et al. 2017). In theory, farms that only use BNF as a nutrient source should show negative budgets for all nutrients besides N. Another plausible source of variation could be the yield level of a farm. Farms with high yield levels often tend to have higher nutrient surplus, especially for N, due to higher external inputs to sustain stronger crop growth, and connected to a lower nutrient use efficiency at higher nutrient levels (law of diminishing returns). Therefore, very intensively managed systems like vegetable farms usually have higher budgets of N, P, and then arable farms (Watson et al. 2002a; Zikeli

et al. 2017). Further, variation between studies from countries, but also within a country can also be detected (Padel et al. 2013; Reimer et al. 2020). One explanation could be structural differences. (e.g. intensity of management, use of external inputs). Therefore, in the present study two regions with different structural characteristics regarding the magnitude of use of external inputs were investigated.

In addition, most research has been conducted for N, P and K, while very few studies have been studying magnesium (Mg) and S budgets. The literature review by Reimer et al. (2020) revealed that only five other studies have been conducted on Mg and only two on S budgets of organic farms in Europe, but only one of these, a study of Mg budgets by Fliessbach et al. (2000) focused on arable farms. The rest investigated dairy, vegetable or mixed farms, which shows that there is a clear need to improve the knowledge of the status of the art regarding the Mg and S budgets across the organic sector. Even less studies investigate all five nutrients at the same time. However, this is of high importance to evaluate the imbalances among the different nutrients, as there is often a surplus of one nutrient coupled with a deficit of another (e.g. Zikeli et al. 2017; Möller 2018). Finally, there is a limited amount of studies which calculate farm gate nutrient budgets for organic arable farms (Klem et al. 2007; Goulding et al. 2008; Küstermann et al. 2010; Nowak et al. 2013a), while the major focus of research was on dairy farms (e.g. Hege et al. 2003; Haas et al. 2007).

The main objective of this study was, therefore, to identify which nutrient inputs are being used on organic farms and potential nutrient imbalances by investigating farm gate budgets for N, P, K, Mg and S as well as the main nutrient input types of organic farms in two regions of Germany of contrasting management intensity (e.g. magnitude of use of external inputs). The focus was on stockless or mixed farms with a low stocking rate ( $< 1 \text{ LU ha}^{-1}$ ), since these farms have a stronger limitation of nutrient availability. We further examined factors responsible for differences in nutrient budgets between farms. As the yield gap in organic farming is often related to nutrient deficits (Askegaard et al. 2011; Rööös et al. 2018), we evaluated whether farm gate nutrient budgets are correlated to yield levels, in order to determine if reduced yields are caused by an under-supply of nutrients or by misdistribution and losses of nutrients within farms or other non-nutritional factors.

We finally explored the relation between available nutrient contents in the soil and (1) farm nutrient budgets and (2) the time since conversion to organic farming. The results help us assess the sustainability of current fertilization management in organic farming in ensuring long term soil fertility.

The following hypotheses were tested:

- (1) The nutrient budget of organic farms in Germany is determined (in order of decreasing importance) by (i) the proportion of N inputs supplied through cultivation of legumes, (ii) the average yield of the main crops grown on the farm, (iii) the animal density measured in animal units per area, (iv) the localization of the farm (southern or northern Germany), and (v) the crops (cereal and legume based farms vs. farms with field vegetable cropping).
- (2) Soil nutrient availability, especially P availability, is correlated to the nutrient budgets and decreases with time since conversion to organic farming.

## Materials and methods

### Farm selection

Ten farms in each of two different regions of Germany were selected for this study, (Table 1). The first region is located in Lower-Saxony (4.1% of agricultural area, 5.3% of organic farmers; average organic farm size 55.1 ha (BLE 2018; Statistisches Bundesamt 2019)), more specifically between the cities of Hannover and Göttingen, hereafter referred to as the northern region. The second region was located in Bavaria (11.0% of agricultural area, 11.7% of organic farmers; average organic farm size 34.7 ha (BLE 2018; Statistisches Bundesamt 2019)), hereafter referred to as the southern region. Here, four farms were located close to the city of Landshut in the southern part of the federal state of Bavaria and six farms between the cities of Würzburg and Bad Kissingen in the northern part of Bavaria. The farms were selected to represent the arable or mixed organic farming systems that are below 1 LU ha<sup>-1</sup>. The farms vary in years under organic farming, cultivated crops, size, soils and animal husbandry. Farms were contacted through personal contacts or the advisory service of Naturland

e.V.. All the farms were either certified by Naturland e.V. or Bioland e.V., the two main German organic farmer organizations.

### Data collection

Semi-structured interviews were conducted with the farmers to understand their nutrient management and to collect data for the calculation of farm gate nutrient budgets for N, P, K, Mg, and S. The amounts of nutrients in all imported fertilizers, soil amendments, seeds, animals, feed, and any other nutrient inputs yielded total nutrient inputs, and the amount of nutrients in all sold plant and animal products as well as any other sold by-product were compiled as total nutrient outputs. The amounts recorded by farmers were multiplied by their nutrient contents. If on-farm records of nutrient contents were available, they were used. If not, standard values were used (Supplementary Table 1). The amount of N input due to BNF was assessed for each crop type individually and yield-dependently, as suggested by Bachinger et al. (2013) for clover grass and by Kolbe (2008) for all other crops. Due to uncertainties remaining in the calculation of BNF, a sensitivity analysis was performed. Anglade et al. (2015) found in their review of published yield related BNF rates a variation of  $\pm 13\%$ , therefore the N input derived from BNF was changed by  $\pm 10\%$  or  $\pm 20\%$  to simulate the effect on nutrient budgets. The N farm gate budget, as well as the proportion of N input from BNF was then calculated with the changed BNF input values for each region and over all farms and compared to the original values.

Budgets were calculated for the cropping seasons of 2014/15, 2015/16 and 2016/17 (September till August). A Spreadsheet tool was designed to record data and calculate the budgets (“Nutri gadget—Hohenheimer organic nutrient farm gate budget calculator”). The tool is available online (<https://orgprints.org/38025/>). Further, descriptive characteristics of each farm (Table 1) were collected.

### Soil sampling and analysis

Soil samples were taken once from three fields of each farm in autumn of 2018. The fields were chosen by perceived importance, as assessed by the farmer—this entailed the largest field, which had been under

**Table 1** Summary of the main characteristics of the selected organic farms. Farms 1–10 are located in northern region and 11–20 in southern region. (YOC = year of conversion to organic farming, FM-Coop = fodder-manure-cooperation, LU = livestock units (appr. 500 kg live weight))

#	Cropped cultures	Animal husbandry		YOC	Area (ha)		FM-Coop	Major soil type (pH/C <sub>org</sub> -range)	LU (LU ha <sup>-1</sup> )
		No	Yes		Sum	Arable			
1	cereals, legume, sugar beets	No	Yes	2009	323	317	6	Clay-loam (7.1–7.4 / 1.6–3.8%)	0.00
2	cereals, legumes, potatoes, root vegetables	Laying hens	Yes	1983	190	185	5	Loam (6.4–7.0 / 1.2–1.6%)	0.48
3	cereals, legumes	No	Yes	2012	43	40	3	Sandy loam (6.3–7.2 / 1.1–1.3%)	0.00
4	cereals, legumes, potatoes	Laying hens	Yes	2006	50	50	0	Sand (5.0–5.5 / 1.9–2.8%)	0.08
5	cereals, legumes, potatoes, carrots, field vegetables	No	Yes	1989	181	180	1	Loess loam (6.3–7.2 / 1.1–1.6%)	0.00
6	cereals, legumes, potatoes, root vegetables	No	Yes	2001	363	354	9	Clay-loam (6.9–7.0 / 1.5–1.7%)	0.00
7	cereals, legumes	Laying hens	Yes	2014	24	23	1	Loess loam (7.3–7.4 / 1.4–2.4%)	0.17
8	cereals, legumes	No	No	1999	64	61	3	Silty loam (6.8–7.3 / 1.3–2.3%)	0.00
9	cereals, legumes, potatoes, root vegetables	No	Yes	2002	422	360	62	Loam (6.9–7.4 / 1.1–1.2%)	0.00
10	cereals, legumes	Dairy cattle	No	1995	40	33	7	Clay-loam (6.2–6.7 / 1.1–1.2%)	0.94
11	cereals, legumes	Suckler cows	No	1998	87	57	30	Loamy sand (4.8–6.3 / 1.4–2.3%)	0.39
12	cereals, legumes	No	No	1996	30	22	8	Loess loam (5.1–6.1 / 1.4–1.6%)	0.00
13	cereals, legumes	No	No	1999	48	46	2	Sandy loam (6.0–6.6 / 1.5–1.9%)	0.00
14	cereals, legumes	No	No	1993	54	44	10	Sandy loam (6.5–6.6 / 1.7–2.7%)	0.00
15	cereals, legumes	Laying hens, suckler cows	No	1987	15	10	5	Loamy sand (6.1–6.8 / 1.3–1.6%)	0.66
16	cereals, legumes	Laying hens, suckler cows	No	2009	125	85	40	Sandy loam (6.9–7.1 / 1.2–1.3%)	0.70
17	cereals, legumes	No	No	1991	105	105	0	Clay-loam (7.2–7.4 / 1.7–2.2%)	0.00
18	cereals, legumes, field vegetables	No	Yes	1991	64	62	2	Clay-loam (6.7–7.3 / 1.3–1.6%)	0.00
19	cereals, legumes	Suckler cows	No	1991	95	55	40	Sandy loam (6.0–6.6 / 1.2–1.7%)	0.50
20	cereals, legumes, root vegetables	No	Yes	2009	119	115	4	Clay-loam (7.1–7.4 / 1.2–1.6%)	0.00

organic production for several years, and which can be seen as representative of the normal crop rotation of the farm. Ten subsamples per field were taken to a depth of 0.3 m and homogenized to obtain one composite sample per field. Samples were analyzed for pH, total carbon (C) and organic carbon ( $C_{\text{org}}$ ), total N content, as well as the extractable amounts of P, K and Mg.

Soil pH was measured in a suspension with  $0.01 \text{ mol l}^{-1}$  calcium chloride solution (VDLUFA 2016) and measured with MPC227 Dual Purpose Conductivity/pH/T Meter by METTLER TOLEDO. Mg was extracted with a  $0.0125 \text{ mol l}^{-1}$  calcium chloride solution (VDLUFA 2016) and measured with the Agilent 5110 ICP-OES. Extractable P and K were extracted using the calcium acetate lactate CAL solution (0.05 M calcium-acetate, 0.05 M calcium-lactate, adjusted to pH 4.1 with acetic acid (VDLUFA 2016)). Concentrations of P were analyzed colorimetrically (ammonium vanadate/molybdate) through spectrophotometric determination (540 nm, Hitachi U-2900 Double-Beam UV-Visible Spectrophotometer). K was measured directly in the CAL-extract through flame spectrometry (Eppendorfer ELEX 6361). Total C and N were analyzed by combustion (vario MAX cube, elemental). Organic C was determined through acid-digestion (hydrochloric acid) of inorganic C followed by the determination of  $C_{\text{org}}$  content as described above. Total P content was extracted by *aqua regia* and measured with the Agilent 5110 ICP-OES (VDLUFA 2016).

## Statistical analysis

### Analysis of farm gate budgets

Statistical analysis was carried out using the *R environment for statistical computing* (R Core Team 2018). Detailed information on R version and citations for used packages, as well as the R scripts used, are available online in the R code.

Average nutrient balances over three years were calculated for each farm. Descriptive statistics were performed on the nutrient budget data using the *stats* package. Input/output ratios, i.e. nutrient use efficiencies, were calculated for N, P, K, Mg, and S using Eq. 1:

$$\text{Input/output ratio} = \frac{\text{Nutrient Output}}{\text{Nutrient Input}} \quad (1)$$

All inputs were grouped into different categories (BNF, organic manures (all animal manures and digestates derived from organic farms), conventional manures (all animal manures and digestates derived from conventional farms), recycled fertilizers divided into plant based fertilizers (e.g. composts, spent mushroom substrate, vinasse, potato protein liquid) and animal based fertilizers (e.g. hair meal pellets), permitted mineral fertilizers (e.g. patent kali or lime) and, seeds, bought live animals, and feed).

Correlations among the different nutrient budgets were calculated using Pearson's *r* as the correlation coefficient. They were tested against a correlation of  $r = 0$ . Calculations were performed using the *psych* package. To determine the influencing factors, a linear mixed model (Eq. 2) was designed, using the *lmerTest* package:

$$\begin{aligned} \text{Nutrient budget} &\sim \text{Area} + \text{Region} \\ &+ \text{Cropped cultures} + \text{Livestock units} \\ &+ \% \text{ of N input by BNF} \\ &+ \text{farm yield as total nutrient output of the farm} \\ &+ \text{assessed year} \end{aligned} \quad (2)$$

As an effect size measure,  $\eta^2$  was calculated using the *lsr* package. Before analysis, all data was checked for variance homogeneity and normal distribution using visual assessment of the residual vs. fitted plot and normal Q-Q plot. Results were plotted for better visualization using the *ggplot2* package.

### Analysis of soil data

Descriptive statistics were performed using the *stats* package. The extractable contents of P, K, and Mg were sorted into groups according to the German VDLUFA standards (A and B: undersupplied, C: optimal, D and E: oversupplied (KTBL 2015; VDLUFA 2018)). As with the farm gate nutrient budget data, correlations using Pearson's *r* were performed for the soil data using the *psych* and *corrplot* package. To analyze if farm gate nutrient budgets were correlated to the soil nutrient contents, linear regressions between soil nutrient content and farm gate nutrient budgets, as well as total farm input



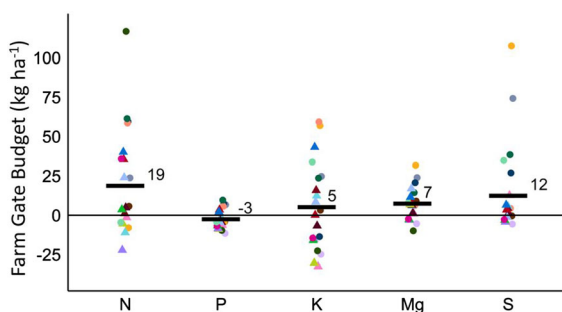
and output were performed using the *lmerTest* package. In the same way, the time since conversion to organic was related to the soil nutrient contents.

## Results

### Farm gate nutrient budgets

On average, farm gate budgets showed a surplus of N (19 kg N ha<sup>-1</sup>), Mg (7 kg Mg ha<sup>-1</sup>), S (12 kg S ha<sup>-1</sup>), and K (5 kg K ha<sup>-1</sup>) (Fig. 1). Only the P budget had a slightly negative mean (-3 kg P ha<sup>-1</sup>). There was a large variability among the different farms as indicated by the range (Fig. 1) and standard deviation (SD) (SD(N) = ± 36, SD(P) = ± 6, SD(K) = ± 28, SD(Mg) = ± 10, SD(S) = ± 33), although the variability was less pronounced for P and Mg.

The high variance can also be observed in the nutrient inputs per farm (Fig. 2). Farms without external fertilizer inputs showed very low input values of < 1 kg ha<sup>-1</sup> year<sup>-1</sup> for P, K, Mg and S (e.g. via seeds). For N, the minimum input amounted to 26 kg ha<sup>-1</sup> year<sup>-1</sup>, calculated for a farm relying to over 90% on BNF. For all nutrients, the input showed a strong and significant positive correlation with the budget ( $R^2(\text{N}) = 0.71$ ,  $R^2(\text{P}) = 0.59$ ,  $R^2(\text{K}) = 0.53$ ,  $R^2(\text{Mg}) = 0.92$ ,  $R^2(\text{S}) = 0.99$ ). The output varied slightly less. Except for S, the minimum output values derive all from the same farm, where animal products are the main outputs (farm 15). For N, P and K, the output was also strongly positively correlated to the



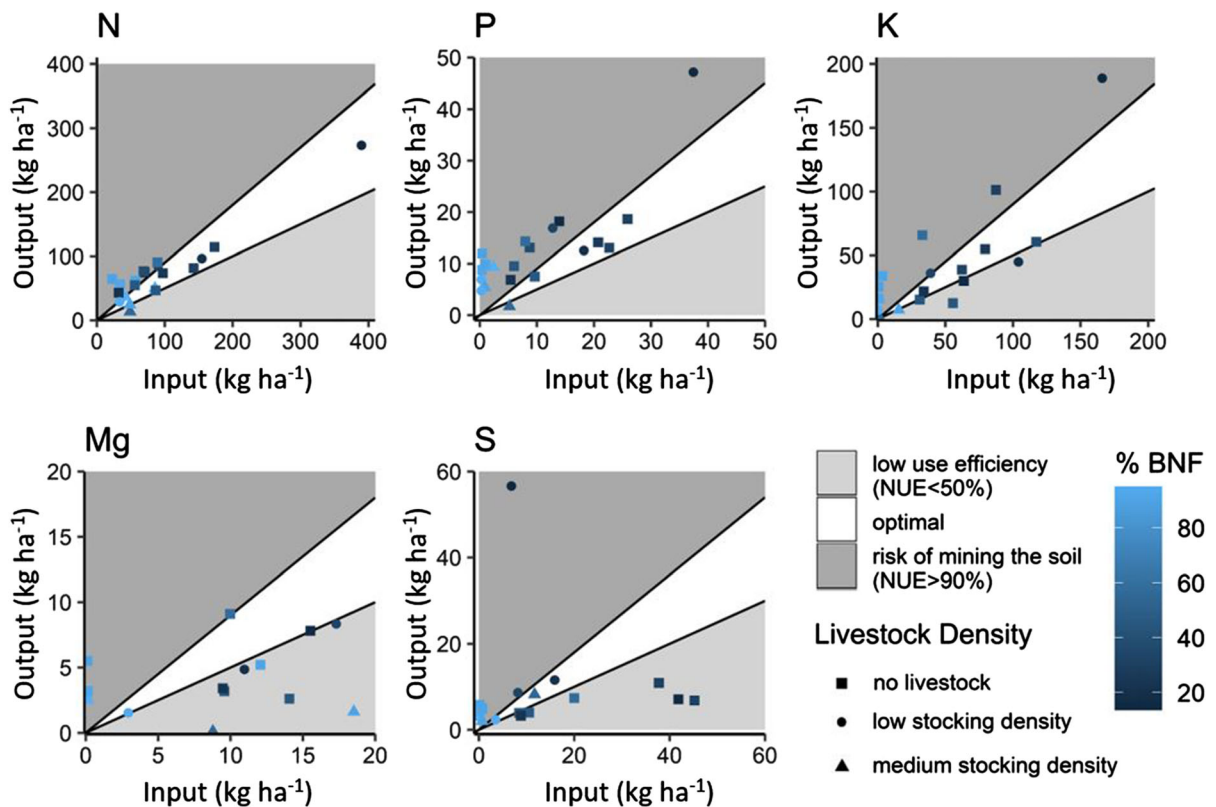
**Fig. 1** Farm gate nutrient budgets for N, P, K, Mg, and S as an average over 3 years in northern Germany (dots) and southern Germany (triangles). Averages of all farms are represented by lines and the numbers provided next to it. Each color represents a specific farm

input ( $R^2(\text{N}) = 0.88$ ,  $R^2(\text{P}) = 0.63$ ,  $R^2(\text{K}) = 0.64$ ), but not for Mg and S (Fig. 2).

The average output/input ratios (N = 0.79, P = 1.25, K = 0.88, Mg = 0.43, S = 0.40) were all relatively high. Since P showed a deficit in the nutrient budget, the input–output ratio is also above 1, by implication the other nutrients show an input–output ratio below 1. Further, the different nutrient budgets were not completely independent from each other. The correlation analysis (Supplementary Table 2) showed that there are some positive correlations between the different nutrient budgets. However, the confidence intervals were quite large. The strongest correlations were found for the S budget, which correlated with all other budgets with a Pearson's *r* above 0.6 for P and Mg. Mg showed also a high correlation to P and K, with a Pearson's *r* above 0.6. This means that above 36% of the variation could be explained. The P budget showed a correlation with the N ( $r = 0.53$ ) and S ( $r = 0.66$ ) budgets. N budgets did not correlate with any other nutrient budgets except P.

Several kinds of inputs were utilized on the investigated farms, but the amount and the variety were different among farms, reflecting the farmers' different fertilization strategy (Supplementary material 1.3). Several farms utilized more than three different kinds of inputs, while five out of 20 farms did not use any external inputs besides seeds and BNF. Biological N<sub>2</sub> fixation was the most important source of N for the farms, supplying on average 55% of N inputs (Fig. 3). The sensitivity analysis (Supplementary Table 3) showed that a change in BNF estimation of ± 10% or ± 20% did not result in major differences in N budgets or proportion of N input derived from BNF. However, the budgets changed by up to ± 7 kg N ha<sup>-1</sup> and the proportion of N derived from BNF by up to ± 4%.

The next largest source of imported nutrients (N = 15%, P = 41%, K = 20%, Mg = 13%, S = 5%, Fig. 3, Supplementary Table 4) were organic animal manures, especially for P. Plant based recycled fertilizers such as composts (household waste or park cuttings), spent mushroom substrate, vinasse products or potato protein liquid were the next biggest input category for all nutrients except N (N = 14%, P = 41%, K = 38%, Mg = 44%, S = 41%, Fig. 3, Supplementary Table 4). The share of recycled fertilizers was especially high for K, Mg and S, due to the high K content of the commonly used plant-



**Fig. 2** Total farm inputs and outputs ( $\text{kg ha}^{-1}$ ) for nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and sulfur (S). Each symbol represents the farm gate average over three years. The lighter the color of the symbols the higher the proportion of N inputs derived from biological nitrogen fixation (BNF). The

symbols represent the livestock density on the farm (no livestock =  $0 \text{ LU ha}^{-1}$ , low stocking density  $\leq 0.5 \text{ LU ha}^{-1}$ , medium stocking density  $> 0.5$  and  $< 1.0 \text{ LU ha}^{-1}$ ). Dark grey area represents farms with a nutrient use efficiency (NUE) above 90%, and light grey area farms with NUE below 50%

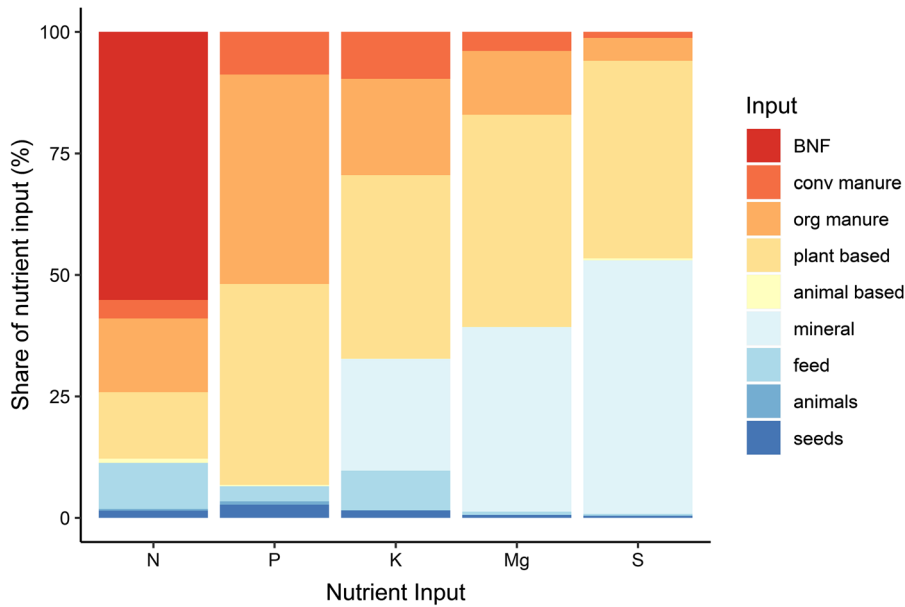
based fertilizers potato protein liquid and sugar beet vinasse, and high Mg and S contents of composts. Contrary, animal based fertilizers accounted just for below 1% of the nutrient inputs. Conventional manures (conventional manures and digestates from conventional farms) had also only a small share of inputs (N = 4%, P = 9%, K = 10%, Mg = 4%, S = 1%, Fig. 3, Supplementary Table 4). For K, Mg, and S the share of mineral sources (K = 23%, Mg = 38%, S = 52%, Fig. 3, Supplementary Table 4) was also relatively high due to the widespread use of limes and S-containing K fertilizers, and, at some farms, of gypsum (S). There were no mineral sources for N and P, since there are no permitted mineral N sources and since not a single farm used rock phosphate as an input. Even though 12 out of 20 farms were stockless, animal feed still showed shares between 3 and 10% for N, P, and K. The feed was

sourced organically on all farms, due to the regulations of the private farmer associations Naturland e.V. and Bioland e.V.. Seeds showed, based on total inputs over all farms, not a high share, but at five farms they were the only input used besides BNF and had, therefore, a share of almost 100% for P, K, Mg, and S inputs at these specific farms.

#### Influences on farm gate budgets

The observed high variance among farm gate budgets from different farms could be explained to some extent by different influencing factors, depending on the nutrient (Table 2). For the P, K, and S nutrient budgets around 50% to 60% of the variation could be explained by the model parameters, compared to only about 30% for Mg and N (adjusted  $R^2$ , Table 2). The factor with the highest influence, except for S, was the proportion





**Fig. 3** Share of nutrient inputs by source of nutrient input averaged across all 20 organic farms. Share is calculated by the total nutrient amount of one input type imported by all farms to

the total nutrient amount imported by all farms. (BNF = biological N<sub>2</sub> fixation, plant based = plant based recycled fertilizers, animal based = animal based recycled fertilizers)

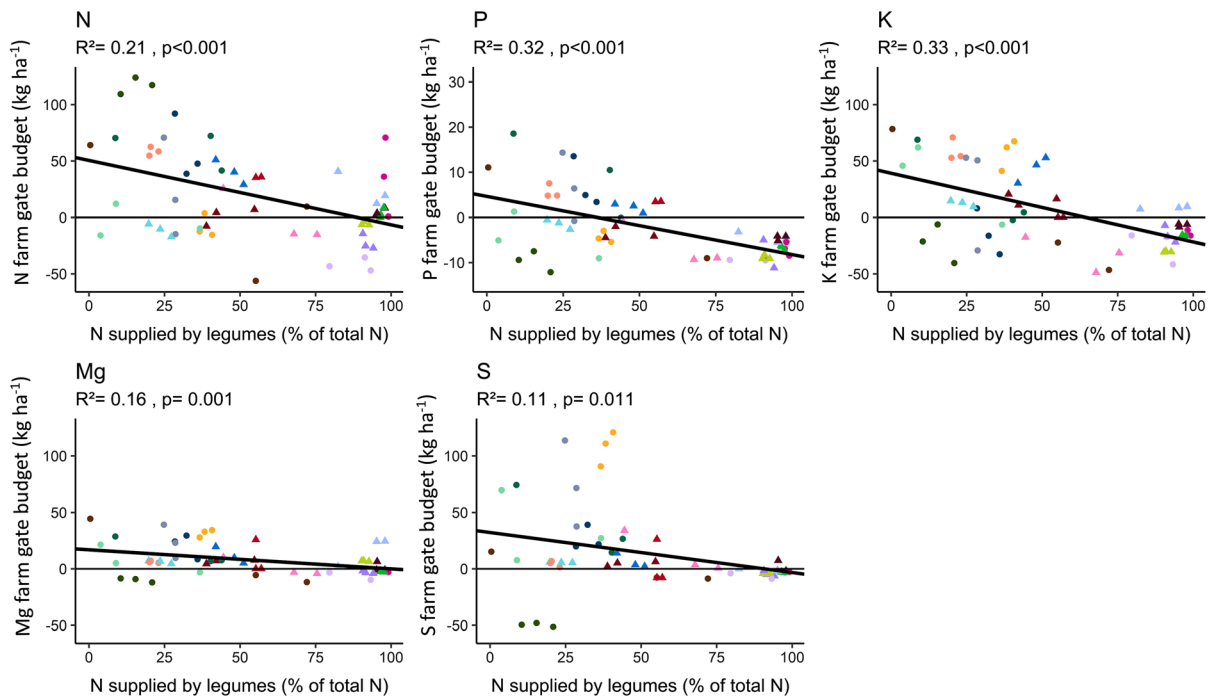
**Table 2** Influencing factors on the farm gate nutrient budgets. *p*-value and effect size, given as  $\eta^2$ , are shown

	N		P		K		Mg		S	
	<i>p</i>	$\eta^2$	<i>p</i>	$\eta^2$	<i>p</i>	$\eta^2$	<i>p</i>	$\eta^2$	<i>p</i>	$\eta^2$
% N from BNF	0.002	0.23	< 0.001	0.39	< 0.001	0.22	< 0.001	0.13	< 0.001	0.03
Nutrient yield	0.526	0.01	0.003	0.04	< 0.001	0.12	0.350	0.01	0.598	< 0.01
Animal units/ha	< 0.001	0.17	0.067	0.01	0.457	< 0.01	0.343	0.01	0.504	< 0.01
Region	0.511	< 0.01	0.246	0.01	0.121	0.02	0.712	< 0.01	0.001	0.01
Cropped cultures	0.666	< 0.01	0.781	< 0.01	0.079	0.01	0.285	< 0.01	0.001	< 0.01
Area	0.100	0.03	0.338	0.01	0.091	0.02	0.007	0.09	< 0.001	0.21
Year	0.577	< 0.01	0.884	< 0.01	0.835	< 0.01	0.756	< 0.01	0.514	< 0.01
Adjusted R <sup>2</sup>	0.32		0.53		0.59		0.34		0.62	

Linear model: nutrient budget ~ % of N input by biological fixation (% N<sub>2</sub> fixation) + nutrient yield + Livestock units (LU/ha) + Region + Cropped cultures (Crops) + Area + assessed year

of N input supplied by BNF (Table 2 and Fig. 4). If a higher share of the total N supply was provided by BNF, the nutrient budgets of N, P, K and Mg became more negative. This relation was the strongest for P, where 39% of the variance could be explained by this factor. The animal density (measured in LU ha<sup>-1</sup>) influenced the N budgets as the second strongest factor. With increasing animal density, the nutrient

surplus increased for N. Contrary, the average achieved yield only had a small influence on the P budget and a medium effect on the K budget, where higher yields were found on farms with higher budgets. The region (northern and southern Germany) did not show a significant effect on the budget except for S, even though the average S budgets showed major difference between regions. The average



**Fig. 4** Relation between percentage of nitrogen (N) input by legumes and the farm gate budgets for N, P, K, Mg, and S (in  $\text{kg ha}^{-1}$ ) in northern Germany (dots) and southern Germany (triangles). The lines show the linear regression

budgets of the northern regions ( $\text{N} = 30 \text{ kg ha}^{-1}$ ,  $\text{P} = -1 \text{ kg ha}^{-1}$ ,  $\text{K} = 13 \text{ kg ha}^{-1}$ ,  $\text{Mg} = 10 \text{ kg ha}^{-1}$ ,  $\text{S} = 23 \text{ kg ha}^{-1}$ ) revealed higher surpluses than in the southern region ( $\text{N} = 7 \text{ kg ha}^{-1}$ ,  $\text{P} = -4 \text{ kg ha}^{-1}$ ,  $\text{K} = 2 \text{ kg ha}^{-1}$ ,  $\text{Mg} = 5 \text{ kg ha}^{-1}$ ,  $\text{S} = 2 \text{ kg ha}^{-1}$ ). The total farmed area also had only a small influence, showing a positive relation between farmed area and budgets for Mg and S. Further, there was a trend that farms which cultivated some kind of field vegetable, like potatoes or carrots, had higher nutrient budgets than farms with mainly cereals and legumes. The assessment year had no influence.

Besides the farm characteristics, the different kinds of inputs also influenced the budgets (Supplementary Table 5). N budgets were only influenced by the use of organic manures, becoming more positive with increasing use of organic manures (measured in  $\text{kg N ha}^{-1}$ ). However, the effect was mainly driven by the use of organic digestates by farm 2. The amount of recycled fertilizers, e.g. composts, plant or animal-based commercial fertilizers, increased all nutrient budgets except the N budget. Increasing amounts of

mineral fertilizer also increased the budgets for K, Mg, and S. Conventional manures and feed imports did not influence any of the nutrient budgets.

#### Soil nutrient contents

The variation between the soil samples was large and some fields had very low nutrient content, as opposed to others (Supplementary Table 6). The soil pH was on average 6.8 but ranged between 4.8 and 7.4. Total proportion of N in the soil was on average 0.16% and ranged between 0.11% and 0.36%, while  $\text{C}_{\text{org}}$  accounted on average for 1.60% (range 1.09% to 3.68%). This resulted in an average C/N ratio of 10, with a range from 8 to 25. Total P was on average  $660 \text{ mg kg}^{-1}$  (range from 365 to  $1048 \text{ mg kg}^{-1}$ ). The extractable amounts of P were on average  $81 \text{ mg kg}^{-1}$  (range from 15 to  $208 \text{ mg kg}^{-1}$ ), resulting in an average share of extractable P to total P of 12% (range from 2% to 26%). The extractable amounts of K and Mg were  $180 \text{ mg K kg}^{-1}$  (range 73 to  $339 \text{ mg K kg}^{-1}$ ) and  $136 \text{ mg Mg kg}^{-1}$  (range from

36 to 380 mg Mg kg<sup>-1</sup>). When grouped according to the supply classes (KTBL 2015; VDLUFA 2018), for extractable soil P 2% were in group A, 12% in B, 27% in C, 42% in D and 18% in E. For K and Mg no samples were found in group A. For K, 10% were undersupplied in group B, 35% in the optimal group C and 43% or 12% in the oversupplied groups D or E. For Mg, 15% were in B, 22% in C, 5% in D, and over half of the samples (58%) in E (Supplementary Fig. 1).

The soil nutrient contents were also correlated with each other (Supplementary Fig. 2). The highest correlations were found between extractable P and share of extractable P to total P content ( $r = 0.92$ ), as well as between N and C ( $r = 0.79$ ) and organic C ( $r = 0.80$ ). Due to a very low content of inorganic C, total and organic C did not differ much from each other. Correlations of about 0.5 were found for extractable P with total P and extractable K, and for total P with extractable K, total N, C and C<sub>org</sub>. The pH level in the soil had also some influence on the different soil nutrient contents. With an increasing pH the amounts of extractable K ( $r = 0.30$ ), and P ( $r = 0.38$ ) as well as the share of extractable P ( $r = 0.40$ ) increased, while the Mg content ( $r = -0.33$ ) and C/N ratio ( $r = -0.38$ ) decreased.

#### *Relationship between nutrient budgets and soil nutrient content*

There was only one significant correlation between the nutrient budgets and the soil nutrient contents (Fig. 5). The N nutrient budget was negatively correlated to the total N content of the soil, although it only explained a small amount of variation ( $R^2 = 0.09$ ). In contrast, total and extractable P, Mg as well as K did not show any relation to the respective nutrient budgets. There was, however, a trend ( $p = 0.057$ ,  $R^2 = 0.06$ ) for the share of extractable P to total P to increase with an increasing budget. There was no correlation between any nutrient budget and C<sub>org</sub> or total C contents in the soil. Further, soil type did not correlate with nutrient budgets.

The correlation analysis of soil nutrient contents and the total farm input or output yielded only few results. An increase in extractable P soil content was found with a higher total farm P input ( $p = 0.02$ ,  $R^2_{\text{adj.}} = 0.24$ ) or output ( $p = 0.03$ ,  $R^2_{\text{adj.}} = 0.19$ ).

#### *Relationship between years of organic management and soil nutrient content*

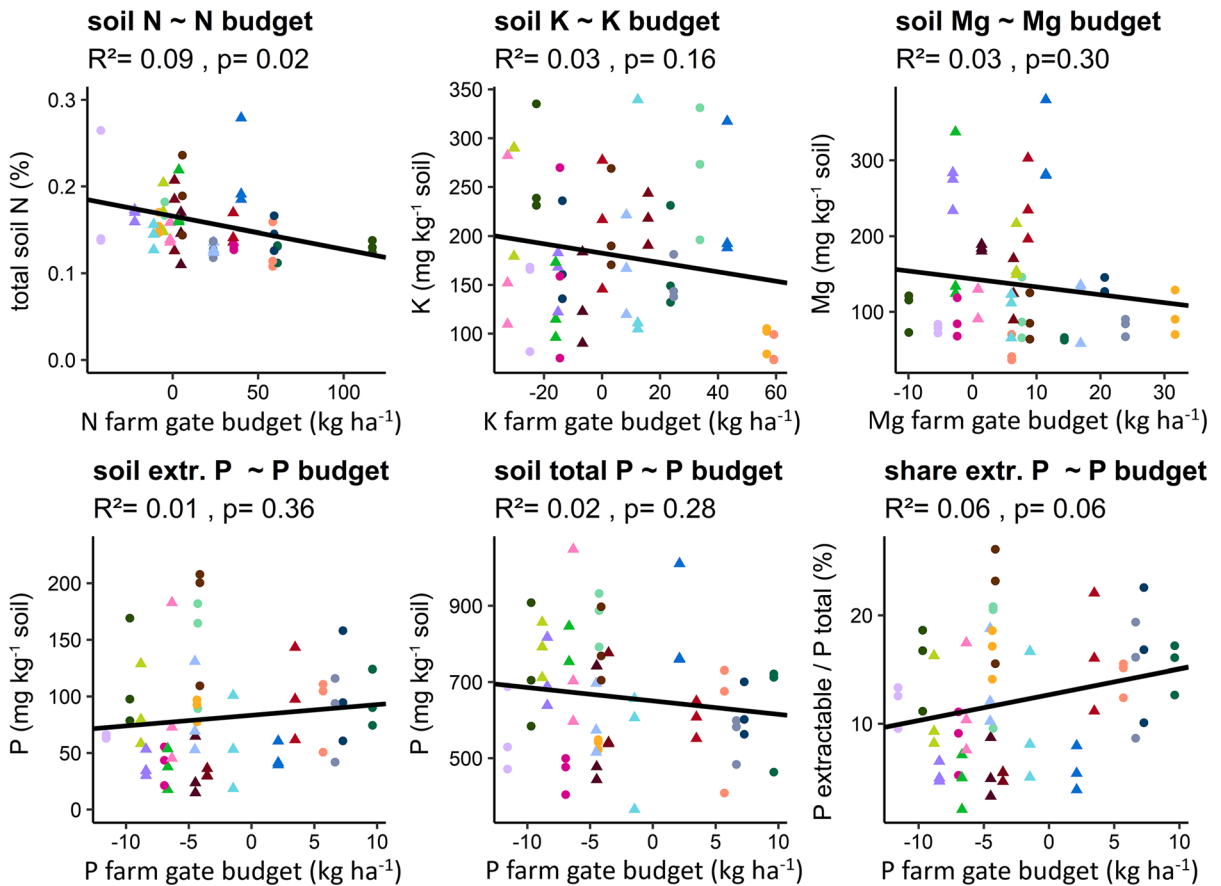
The years since conversion to organic farming influenced only two soil properties: the contents of extractable P and Mg (Fig. 6). Mg content in the soil increased with years since conversion. In contrast, for P, with increasing time of organic management the content of extractable P in the soil decreased. It should be noted that there was a strong decrease until 27 years of organic management (dashed line Fig. 6), while the content seemingly increased for the three farms that have been organic for more than 27 years.

## Discussion

### Imbalances in nutrient budgets of organic farms

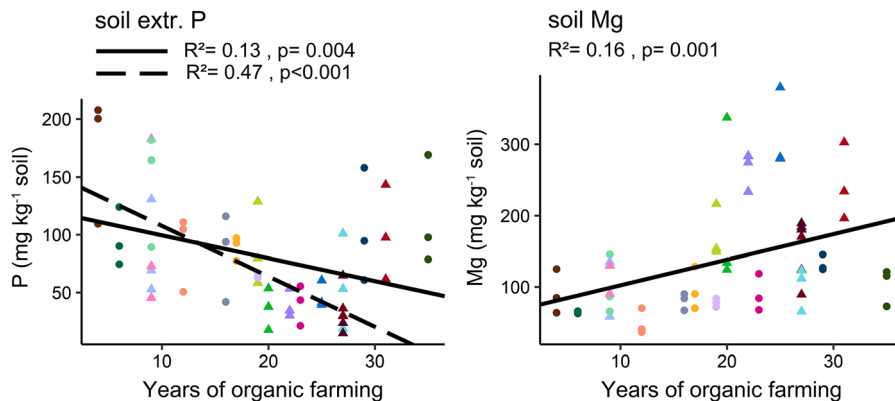
Average farm gate nutrient budgets were slightly positive for N, S, Mg and K, indicating that—across the farming sector—the nutrient management seems to be sustainable for these nutrients. However, none of the inventoried farms had a fully balanced input–output relationship across all nutrients, with a few farms showing positive balances across all major nutrients (5 of 20 farms), while several farms had a deficit of at least one nutrient (N: 8, P: 14, K: 10, Mg: 5, S: 8). This means that almost half of the farms had deficits in more than one nutrient, and about 70% had a deficit in the P budgets. Most inventoried farms showed surpluses for some nutrients, and simultaneously negative budgets for others (14 of 20), while one farm had negative budgets across all nutrients. However, budgets were still correlated with each other, indicating that if a farm lacks one nutrient (besides N) it is very likely to also have deficits in another nutrient (Table 3).

The presented N budget average fits within the range of most reported farm gate N budgets of mixed or stockless organic farms (26 kg ha<sup>-1</sup> Klem et al. 2007; 15 kg ha<sup>-1</sup> Loges et al. 2006; 28 kg ha<sup>-1</sup> Nowak et al. 2013a). For P, both more negative and more positive farm gate nutrient budgets can be found in the literature (−9 kg ha<sup>-1</sup> Korsæth 2012; 10 kg ha<sup>-1</sup> Nesme et al. 2012; 10 kg ha<sup>-1</sup> Nowak et al. 2013a; −9 kg ha<sup>-1</sup> Schmidtke et al. in press). For Mg and S, significantly fewer studies can be found. Our results are very similar to the Mg and S budgets of



**Fig. 5** Relation between farm gate nutrient balance (in kg ha<sup>-1</sup>) and soil nutrient content. Shown are the relations between N budget and total N content in the soil (%), K budget to extractable K (mg kg<sup>-1</sup> soil), Mg budget to extractable Mg soil content (mg kg<sup>-1</sup> soil) and P budget and extractable P soil

content (mg kg<sup>-1</sup> soil), the total P soil content (mg kg<sup>-1</sup> soil), as well as the share of extractable P of total P (%). Dots represent farms in the northern region and triangles farms in the southern region



**Fig. 6** Relation between extractable soil P and Mg and the time the farm has been farming organically in years. Solid line shows the correlation for all farm, dashed line excludes the farms,

which have been organic for more than 27 years. Dots represent farms in the northern and triangles in the southern region

Fliessbach et al. (2000). The S budget found for organic dairy farms in Denmark by Eriksen & Askegaard (2000) on the other hand shows lower values. This might be due to the differences between dairy and mixed or stockless farms. In general, only very few studies on S can be found in literature (Reimer et al. 2020), although S is of high importance in organic farming systems. Sulphur is an essential nutrient for efficient BNF, so long-term S deficits, as determined for farm 8, 11, 12 and 13, reduce the ability of legumes to fix N (Scherer 2008).

The presented Mg budgets are similar to findings by Schmidtke et al. (in press; 12 kg Mg ha<sup>-1</sup>) but lower than findings of Bengtsson et al. (2003; 39 kg Mg ha<sup>-1</sup>). Yet, Bengtsson et al. (2003) investigated dairy farms and not stockless or mixed farms with low stocking density. Mg budgets are usually highly influenced by the amount of lime used on the farm. Depending on soil type and soil pH, more or less lime is needed for an optimal soil conditions, which can also result in different Mg budgets (Bengtsson et al. 2003).

Contrary to our findings, most studies on K report negative nutrient budgets (Fliessbach et al. 2000; Andrist-Rangel et al. 2007; Korsæth 2012; Thorup-Kristensen et al. 2012). This can be explained by the fact that many farms in our study, especially intensively managed potato growing farms, use plant-based recycled fertilizers such as urban compost or by-products from the industry such as potato protein liquid or vinasse as well as patent kali, which contain high amounts of K.

In general, the largest share of inputs was found for biological N<sub>2</sub> fixation (Fig. 3). On average, almost half of the N supply and almost 100% for some farms was supplied by legumes, which is in line with the organic farming principle (IFOAM 2017) and the farmers' reported fertilization strategy (Supplementary material 1.3). Another important fertilizer source were manures from other organic farms, which mostly come from cooperation agreements with other organic farms, showing an alternative option to organize a redistribution of nutrients within the organic system. The share of conventional manures was significantly less than in other studies (Nowak et al. 2013b), due to the compliance with the regulations of the private farmer organization (Naturland e.V. or Bioland e.V.), which limit the use of conventional fertilizers to solid farmyard horse or cattle manures and also set

maximum import limits (Bioland e.V. 2019; Naturland e.V. 2019). Further, no rock phosphate was used in any of the studied farms. Rock phosphate is known to be an inefficient P fertilizer at pH levels above 5.5–6.0 (Möller et al. 2018) and was therefore not used by farmers.

The use of few specific kinds of inputs increased the nutrient budgets. An increase in N budget was only observed in farms using higher amounts of organic manures. Farms with higher inputs of recycled fertilizers, contrastingly, had increased budgets for P, K, Mg, and S, but not necessarily for N. Plant-based recycled fertilizers, like composts, usually have higher contents of P, K and Mg per unit N than other fertilizers like animal manures (Möller and Schultheiß 2014). This strengthens the suggestion by Løes et al. (2017) that recycled fertilizers are an appropriate external input to increase the supply of nutrients beside N in organic farming.

High reliance on biological nitrogen fixation results in nutrient deficits of phosphorus, potassium, magnesium and sulphur

This study also aimed to understand the large differences found between results of nutrient budgets in organic farming reported in the literature. So far, scientific literature mostly identified farm type and livestock density as factors determining variation between farms (Foissy et al. 2013; Reimer et al. 2020). Our study shows that the relative importance of factors influencing farm gate budgets (hypothesis 1) is only partly supported by the presented data. The share of N supplied by BNF indeed determines nutrient budgets in organic farming systems (Table 2, Fig. 4). All farms with a share of N inputs from BNF > 60% had negative P budgets and mostly showed negative K budgets. For Mg and S, a reliance on BNF of over > 80% resulted in negative balances. This correlation can be found in past literature when comparing different studies. Studies that report negative budgets, such as Schmidtke et al. (in press) or Korsæth (2012) also investigated farms with high reliance on BNF. In contrast, studies that report high nutrient surpluses, such as Berry et al. (2003) or Nowak et al. (2013a, b) investigated mostly farms with a lower reliance on BNF.

We therefore conclude that higher N self-reliance of a system, as indicated by the share of legume-N in

relation to the total N inputs, leads to higher risk of nutrient deficits especially for P, K, Mg and S. This implies that adequate amounts and mixtures of external fertilizers are needed to replenish nutrient offtake of these farms, in context of the inputs obtained via BNF. The lower the N/P ratio of the sold fertilizers and the higher the unproductive N losses (nitrate leaching, ammonia volatilization etc.), the higher the need for N inputs via BNF and vice versa. For K, Mg and S, fertilizers such as patent kali, vinasse and potato protein liquid, elemental sulphur and lime are available but not available everywhere.

Furthermore, and crucial for the future development of the organic sector, is the need for P sources permitted in organic farming that are more efficient than rock phosphate, which is not suited for alkaline and slightly acidic soils. These alternative fertilizers could be provided from recycling products from the urban waste streams, some of which are currently allowed (e.g. based on source separated organic household wastes, or from food industry). However, the current availability of source separated organic household wastes in Germany accounts for approximately 5,000,000 Mg compost and 800,000 Mg digestates (Möller and Schultheiß 2014). Based on the total farmland area in Germany, the nutrients in these sources account for approximately 3.0–3.5 kg N, 0.5–1.0 kg P and 2.0–2.5 kg K and 0.7–1.2 kg Mg per ha farmland, indicating their very restricted availability compared to the theoretical nutrient recycling needs. Therefore, there is a need to make other sources available for use in organic farming. The main potentially P recycling source is sewage sludge, but sewage sludge based fertilizers, e.g. struvites, are at present not permitted in organic farming (Möller et al. 2018).

The regional differences in nutrient budgets could also be explained by different reliance on N from BNF (Fig. 4). Therefore, it is not a regional difference but rather a management difference. The different management strategies could, however, be caused by different infrastructural characteristics. In the Northern region the regional availability of external nutrient sources is higher, as well as the farm size and the intensity of farming activities. For example, the availability of chicken manure and of spent mushroom substrate is higher in the Northern region, which lowers the transport costs, resulting in a higher use of external inputs and hence higher nutrient budgets. This

illustrates that even if farmers would like to use more inputs, as stated by many farmers, in the northern and southern region alike, in the interview (Supplementary material 1.3), regional availability can be an obstacle. Thus, regional adapted solutions and not only national plans might be necessary.

The farm yield levels, measured as total nutrient output of the farm, did not have the expected effect on the nutrient budget. There was no significant influence except for the P budget, which might have been significant but is not relevant due to a  $\eta^2$  of below 0.1. Nonetheless, the total farm output was highly correlated with the input. In general, organic farming systems are able to achieve high yields with relatively low nutrient surpluses due to a high nutrient efficiency (Drinkwater 2005), but simulations have also shown that an increased N supply through manure or other organic fertilizers can increase yield even without additional losses (Doltra et al. 2011). These farm case studies show that it is possible for organic farms to increase their productivity through increased fertilizer input while not necessarily causing higher nutrient surpluses.

Similar to findings in the literature, stocking rate had a strong effect on the N budgets (Giustini et al. 2008; Foissy et al. 2013), but low effect on the other nutrient budgets (Nesme et al. 2012; Ruane et al. 2013). Livestock production bears different risks of high N losses, especially ammonia losses from manure storage (Webb et al. 2013). These losses are not calculated in our budgeting method. So, even though higher N surpluses are found for farms with higher stocking density, it does not necessarily imply that more N is available for plants but just that losses within the farms are higher. Further, farms with ruminants tend to have large surface area for forage production, which increases the N input through BNF (Foissy et al. 2013).

The type of crops produced on a farm only had an effect on the K budget. Especially potatoes and field vegetables are K demanding crops. Farmers are generally aware of this fact and therefore supply sufficient K, mainly in the form of mineral fertilizers such as magnesium-containing sulfate of potash.

The size of the farm influenced only the S budget, which might be coincidental, as some of the larger farms had high imports through elemental S or from compost or spent mushroom substrate.



## Organic farming depletes the soil of phosphorus in long-term perspective

On average, the tested soils were well supplied with nutrients according to the German standard soil nutrient classification (KTBL 2015; VDLUFA 2018). However, the range between farms and even between fields within farms is very large. For almost all measured soil properties there are fields that are not in the optimal range for crop production, which indicates former soil mining. Other fields show a clear excess, which can have negative effects on the environment due to a higher risk of nutrient leaching. Ruane et al. (2013) also detected this high variation for soil P contents between and within farms and suggested that even though soil testing is common for farmers, they are not aware of this problem or do not make sufficient use of the soil testing results.

The soil parameters correlated less with each other than expected, which indicates the former imbalances of nutrient inputs to the soil and the need for farm-specific solutions. The correlation between carbon contents and N content in the soil also confirms the statement by Berry et al. (2002) that in organic farming systems, a large portion of N is stored in the organic matter. Since there was not a strong relationship between total P and extractable P, the total P content might be more dependent on soil type and the ability of the soil to sorb P as indicated in previous papers (Magid et al. 1996). The share of extractable P to total P did also not correlate with total P, emphasizing this relationship. The share, however, was only dependent on the extractable amount of P in the soil.

The results of our study can only partly support the second hypothesis, that soil fertility status is correlated to farm gate nutrient budgets and decreases with time. We did not find any relation between soil nutrient status for P, K, Mg, nor did any budget influence the amount of carbon in the soil. Similar results were found in the literature (Watson et al. 2000). Korsath (2012), however, points out that substantial soil mining can occur for N, P, and K before the common soil analysis method can detect them. Missing nutrients, such as K, can be—temporarily—supplied from soil reserves or lower soil layers depending on soil type (Andrist-Rangel et al. 2007). Nutrient budgets are therefore more suitable to detect these early stages of soil depletion. Further, differences in initial values

before converting to organic farm management can mask the effect across different farms.

The majority of the reported results, however, show a relationship between P budget and soil content (Blake et al. 2003; Ruane et al. 2013; Ohm et al. 2017). In our results, this is only indicated by the trend that with lower P budget the share of extractable P to total P is decreasing. If soil P is depleted due to higher offtake than input, the more labile fraction of P in soil will deplete first while the more stable P fractions do not change (Blake et al. 2003).

Although not very strong, there was an unexpected, significant negative correlation for total soil N with the N budget. Farms with high N surpluses were primarily farms that also had rather intensive crops such as potatoes or field vegetables. These crops also demand a higher intensity of tillage, which leads to lower contents of C in the soil (Holland 2004), and increases N mineralization (Peigné et al. 2007). Thus, it could have reduced the amount of N in the soil. Another reason might be, the increase in N losses, particularly through leaching, with increasing N surpluses, which then depletes the soil of N (Berry et al. 2002).

The mining of any nutrient from the soil through negative budgets does not always need to be interpreted negatively. If soil nutrient levels, for example of P, exceed the optimal range due to former high P application leading to high amounts of so-called legacy P, slightly negative budgets and the uptake of soil P might be favorable with regard to environmental impacts. Nonetheless, if P availability in the soil is already low, negative P budgets are not suitable for sustaining soil fertility. For some farms of this study, soil P limiting crop production is a current problem or will become problematic in the short term and not just in the long term as proposed by some studies (Steinshamn et al. 2004; Cooper et al. 2018).

The results of this study also suggest that the risk of low soil P increases with the time under organic management. Thus, the 5th hypothesis of decreasing nutrient availability with increasing time since conversion can be supported for P. In contrast, the other nutrients were not affected by the time under organic management. Even though there was a significant relationship between soil Mg content and the time since conversion to organic management, this relation is not necessarily relevant since the effect is mainly driven by three farms (no. 12, 14, 15), which have very high soil Mg contents compared to all other farms,

probably due to geogenic reasons. In contrast to our results, Mäder et al. (2000) only determined a decrease with time for K but not for P or Mg. Still, there is a knowledge gap of how exactly organic farming affects soil nutrient status in the long-term, as pointed out 20 years ago by Fortune et al. (1999).

### Limitations

Farm gate nutrient budgets are an established tool for the analysis of nutrient supply in organic farming and are able to point out nutrient deficits or surpluses on a farm. Nevertheless, they also hold some uncertainties and have limitations. First of all, a large dataset is needed to compile them, since all in- and outflows need to be quantified. Thereby, the nutrient content of the different products can vary slightly from standard values. This can and should be corrected if farm-specific data on the nutrient contents is available. Another high uncertainty lies in the calculation of the BNF, since the fixation rate is highly dependent on the yields and other environmental factors such as soil mineral N content or soil moisture (Anglade et al. 2015). Using yield specific data and sensitivity analysis, as done in this study, helps to reduce and assess the uncertainties but does not eliminate them. Furthermore, certain losses, e.g. leaching of N and S or volatile losses of ammonia, and inputs, e.g. atmospheric deposition, were not included in our calculations. Since losses—depending on soil type and application—are usually higher than atmospheric deposition, for N and S the supply to the plants might be lower than the budgets suggest.

The soil nutrient measurements also hold some uncertainties. Since the samples are taken from farmers' fields and not in an experimental plot, they can be subjected to a high degree of variability throughout the field and throughout the farm. Collecting samples from more than one field and on several points of one field, as done in this study, can help to lower the variation, yet a certain degree of uncertainties will remain.

In addition, this study is based on case studies of low stocked mixed farms and stockless farms. It does not represent the whole organic farming system in Germany, but rather a certain type of farms within the system.

### Conclusion

The results of our study show that the reliance of organic farming systems on BNF is not sustainable in a long-term perspective. In addition, the rationale that solid animal manures or composts are balanced fertilizers that supply nutrients according to the stoichiometric needs of plants will result in deficits of one nutrient while others will be oversupplied. Nutrient imbalances in nutrient budgets—in terms of surpluses for one nutrients combined with deficits of other nutrients—are a common finding in organic farming systems. Especially P scarcity is a universal problem in arable organic farming. An adequate farm-specific mixture of different external inputs in combination with BNF, which fits the nutrient requirements of the farm, might be a suitable solution. In order to achieve this goal, appropriate nutrient inputs that allow recombination of macro-nutrients are needed for organic farms. Fertilizers recycled from different waste streams would facilitate nutrient management in organic farming systems once they are permitted for use and ubiquitously available. Therefore, we need further research on the application and regional availability of recycled fertilizers in the context of organic farming systems.

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

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### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Data availability** The data set and the R script are available online (<https://osf.io/uhd fz/>).

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