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Meta-analysis of nutrient budgets in organic farms across Europe

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Abstract Nutrient supply to organic farms is a highly discussed topic in Europe, due to the restricted availability of external fertilizer resources and the use of contentious inputs. To optimize the flow of nutrients throughout the organic farming system, it is firstly necessary to obtain valid data on the nutrient status of organic farms. Nutrient budgets are a valid tool to investigate the nutrient demand or surplus of a system. However, there is currently no comprehensive overview of nutrient budgets of European organic farms. We therefore carried out a meta-analysis on 56 individual studies that reported either farm-gate or soil surface budgets. The analysis showed an imbalance between nutrients, a general surplus of nitrogen (45 kg N ha^{-1} year^{-1} [95% confidence interval (CI) 30, 61]), magnesium (16 kg Mg ha^{-1} year^{-1} [− 9, 40]) and sulfur (45 kg S ha^{-1} year^{-1} [− 29, 118]), a balanced phosphorus budget (0 kg P ha^{-1} year^{-1} [− 2, 2]), and a deficit for potassium (− 12 kg K ha^{-1} year^{-1} [− 21, − 3]). We observed large differences between farms that could be partly explained by farm type and budgeting method. Arable and mixed farms showed lower nitrogen, phosphor, magnesium, and sulfur budgets than dairy/beef farms or even vegetable farms, while all farm types besides dairy/beef farms showed deficits for K budgets. Further, farm-gate budget studies yielded higher budgets than soil surface budgets. Variations between studied countries could also be detected, but the coverage and comparability are low due to differences in studied farm types and budgeting method.

Keywords Nutrient balance · Farm-gate · Meta-analysis · Soil surface · Organic farming · Europe · Farm type

Introduction

Nutrient management systems of conventional and organic farming differ from each other significantly. While conventional nutrient management relies strongly on external mineral fertilizer inputs, the principal of nutrient management in organic farming is based on biological nitrogen fixation (BNF), nutrient cycling within the farm, and nutrient recycling from urban and other waste streams (Watson et al. 2002a; IFOAM 2017). The use of external fertilizer inputs in the organic farming sector is being controversially discussed. The goal is to limit the amount of contentious inputs such as fertilizers derived from conventional agriculture, like conventional manure (Oelofse et al. 2013), and finite resources like rock phosphate. However, any farm

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export of nutrients like phosphorus (P), potassium (K), magnesium (Mg), and sulfur (S) through sold products should be replenished on the long-term perspective in order to ensure sustainable nutrient management. The goal of sustainable nutrient management should be therefore to have a balance between inputs and outputs, since on the one hand, there is a risk of environmental pollution, e.g., through losses of nutrients via leaching or runoff, when inputs outweigh the outputs (Blicher-Mathiesen et al. 2014). On the other hand, there is the risk of soil nutrient depletion and loss of soil fertility (Løes and Øgaard 2001; Cooper et al. 2018), when the opposite is the case. Specific studies provided some indication for nutrient imbalances (Berry et al. 2002; Zikeli et al. 2017; Cooper et al. 2018), and that farm type represents an important factor responsible for the variation between farms (Watson et al. 2002a; Ohm et al. 2017). Thereby, stockless arable farms are expected to have lower surpluses of nutrients than stocked farms. Giustini et al. (2008) and Foissy et al. (2013) found a strong relation between stocking density and nitrogen (N) budgets. Vegetable farms are more prone to high nutrient surpluses due to high fertilizer inputs, imbalances between nutrients, and the need for high yields and economic returns due to high production costs (Zikeli et al. 2017). However, there is a lack of studies providing an overview about the situation across the entire organic sector in Europe.

Nutrient budget studies are a valid tool to evaluate the nutrient management strategy of a farm and to quantify potential nutrient oversupplies or demands in agricultural systems (Watson et al. 2002b). Nutrient budget calculations quantify each nutrient input and output of a farming system. Watson et al. (2002b) describe three different methods of budget calculations: *farm-gate*, *soil surface*, and *system budgets*. These methods differ mainly in the boundaries that are drawn to define the agricultural system being investigated. Farm-gate budgets consider the whole farm, while soil surface budgets, also called *field budgets*, only take into account inputs and outputs to one or more fields. System budgets consider the whole production sector of the agricultural system. These types of budgets are more aggregated and go beyond the farm level and they will not be considered for the present study.

This study aims to provide a comprehensive overview of nutrient budgets of different organic farm types across Europe, by combining and meta-analyzing the results of previously published literature. In this study, the soil surface and farm-gate nutrient budgets of N, P, K, Mg, and S will be examined with regard to the farming type (vegetable, cattle/dairy, mixed or arable farms) and investigated countries in Europe.

Materials and methods

A survey of CAB-listed literature, published between 1990 and 2019, was conducted to identify papers that report nutrient budget studies of organic farms in Europe. The following search terms were used in various combinations: farm-gate/farm/nutrient; budget/balance/flows; organic/bio-dynamic/ecological, and Europe. The search resulted in 1827 identified studies. The data from these studies was subsequently scrutinized according to criteria of thematic fit, language requirements (English or German), and availability of descriptive or statistical effects. A study was seen as thematically fitting if it met the following criteria: (1) must have quantified nutrient budgets of N, P, K, Mg, and/or S, (2) the nutrient budgets must be from organically managed farms, fields, or experimental stations, (3) only arable, dairy/beef, mixed (all types of animals), and vegetable farms were considered, and (4) the farms must be located in the geographical region of Europe. Further, only original studies were included; review articles were not taken into account. Additional papers were found by searching the reference lists of already selected papers and by recommendations of experts. Additionally, two unpublished studies were included. Where data for means and standard deviations were missing but ranges were given, estimations after Walter and Yao (2007) and Weir et al. (2018) were used.

Meta-analyses for each nutrient were performed on the whole data set and subsets of data based on farm type (arable, dairy/cattle, mixed, or vegetable farms), method used for nutrient budget analysis (soil surface, or farm-gate budgets), or country of origin, using the *metaphor* package in *R* (R Core Team 2018) as described by Viechtbauer (2010). The τ^2 parameter was used as a measure of heterogeneity within the dataset. Moderator tests were carried out for the categorical moderator farm type, and budget method separately as well as together with a dummy variable. The R^2 parameter was used to determine the amount of heterogeneity the moderator variables accounted for. An omnibus test was performed to determine if moderators had a significant influence on the nutrient budgets (alpha level 0.05 for the QM test; Viechtbauer 2010).

Results

The literature search resulted in 56 studies from 15 different countries that met the selection criteria (Table 1). Many studies were discarded since they were not available in English or German but were published in the native language of the origin country. Many studies also investigated only one, two, or three nutrients, mostly N, P, and K, and not all of the nutrients considered for this meta-analysis (Table 1). This resulted in a very variable study and farm count across the different nutrients. Most studies and farms were examined for N (44 studies/621 farms), followed closely by P (36 studies/556 farms) and K (32 studies/520 farms). However, only six studies (78 farms) were found for Mg and only three (43 farms) for S. Therefore, a detailed meta-analysis with subsetting for farm types and budget method or a moderator analysis were not performed for these two nutrients. Two studies, Zikeli et al. (2017) and Reimer et al. (under review), considered all five different nutrients at the same (Table 1).

The results of the meta-analysis indicated a surplus of 45 kg N ha^{-1} $year^{-1}$ [95% confidence interval (CI) 30 to 61 kg N ha^{-1} $year^{-1}$] over 44 studies and a total of 621 investigated farms if not differentiated among farm types or budget method (Fig. 1, Supplementary Table 1). The meta-analysis for P resulted in a balanced budget of 0 kg P ha^{-1} $year^{-1}$ [95% CI − 2 to 2 kg P ha^{-1} $year^{-1}$] over 36 studies and 556 investigated farms. Yet for K, there was an overall deficit of − 12 kg K ha^{-1} $year^{-1}$ [95% CI − 21 to −3 kg K ha^{-1} $year^{-1}$] over 32 studies and 520 investigated farms. For both Mg and S, there were surpluses of 16 kg Mg ha^{-1} $year^{-1}$ [95% CI − 9 to 40 kg Mg ha^{-1} $year^{-1}$] and 45 kg S ha^{-1} $year^{-1}$ [95% CI − 29 to 118 kg S ha^{-1} $year^{-1}$] over 6 or 3 studies and 78 or 43 investigated farms, respectively. However, the results for Mg and S do not reflect the whole organic sector due to the low study and farm count and therefore, the different studies should be regarded separately.

For Mg, two studies by Bengtsson et al. (2003) and Zikeli et al. (2017) have noticeably higher surpluses than the other four studies. These two studies investigated a dairy farm or vegetable farms, while the lower budget values were found for arable or mixed farms. Similarly, for S, Zikeli et al. (2017) found very high surpluses (119 kg S ha^{-1} $year^{-1}$) on vegetable greenhouse farms while the other two studies found lower surpluses on arable or dairy farms.

There was a high level of heterogeneity for the meta-analysis of N, P, and K budgets as well (τ^2 in Supplementary Table 2). In order to explain parts of the heterogeneity found for the N, P, and K budgets, the farm type and budgeting method, as well as a dummy variable consisting of the farm type and the budget method, were used as moderators in a separate meta-analysis for each subset. Almost all moderator tests were statistically significant, except of the farm type moderator for the P budgets ($p = 0.0527$, Table 2). However, the moderators varied in their ability to explain the heterogeneity of results. For N, the most important moderation was due to differences in farm type, which explained 26% of the heterogeneity. The data indicated that arable and mixed farms have lower mean surpluses (19 or 18 kg N ha^{-1} $year^{-1}$) than dairy/beef farms (77 kg N ha^{-1} $year^{-1}$), while vegetable farms had the highest surpluses (117 kg N ha^{-1} $year^{-1}$, Fig. 1 and Supplementary Table 1). The same pattern, even if not as strong ($R^2 = 6\%$), was obtained for P, where the means ranged between − 4 kg P ha^{-1} $year^{-1}$ for arable and 24 kg P ha^{-1} $year^{-1}$ for vegetable farms (Fig. 1 and Supplementary Table 1). The observed pattern was different for the K budget. For arable, mixed farms, as well as vegetable farms, we observed deficits between − 44 and − 12 kg K ha^{-1} $year^{-1}$. Only the data for dairy/beef farms provided a slight surplus of 2 kg K ha^{-1} $year^{-1}$. In total, farm type explained 14% of the heterogeneity in K estimates. The budget calculation method showed also some moderation. For N, P, and K, the farm-gate budgets showed higher means than the soil surface budgets (Fig. 1, Supplementary Table 1). Yet, the moderation varied between nutrients, showing higher numerical differences for N budgets than for P and K budgets and different amounts of explained heterogeneity. The R^2 for N was 11% and therefore less than half of the one attributed to farm type (Table 2). For K, the R^2 was also slightly lower, while for P, the R^2 was more than doubled. The strongest moderation, however, was observed when farm type and budget method were combined, except for N where farm type had a 2% higher R^2. For P and K, both variables together were able to explain about 30% of the heterogeneity, which is approximately doubled from what one variable could explain on its own.

Table 1 Overview of studies used in the meta-analysis. N represents the number of investigated farms per study

Study	N	Farm type	Budget kind	Country	N	P	K	Mg	S
Goulding et al. (2008)	1	Farm-gate	Arable	GBR	− 22.6	− 2.6	− 39.2		
Klem et al. (2007)	8	Farm-gate	Arable	DEU	26.1				
Küstermann et al. (2010)	1	Farm-gate	Arable	DEU	35.7				
Nowak et al. (2013)	20	Farm-gate	Arable	FRA	27.6				
Nowak et al. (2013)	19	Farm-gate	Arable	FRA		9.9	1.8		
Reimer et al. (in review)	20	Farm-gate	Arable	DEU	18.9	− 2.8	4.5	7.2	12.2
Cuttle (2002)	1	Farm-gate	Dairy/beef	GBR	157.0	2.0	15.0		
Eriksen and Askegaard (2000)	1	Farm-gate	Dairy/beef	DNK					2.6
Fortune et al. (1999)	3	Farm-gate	Dairy/beef	GBR		7.0	21.6		
Fowler et al. (1993)	5	Farm-gate	Dairy/beef	GBR	9.7	3.4	14.0		
Goulding et al. (2000)	2	Farm-gate	Dairy/beef	GBR	70.2	− 2.0	5.4		
Goulding et al. (2008)	2	Farm-gate	Dairy/beef	GBR	30.7	− 12.1	− 39.7		
Gruber et al. (2001)	1	Farm-gate	Dairy/beef	AUT	4.0	− 3.0	− 34.0		
Haas et al. (2007)	26	Farm-gate	Dairy/beef	DEU	43.0	− 2.8	0.8		
Halberg et al. (1995)	14	Farm-gate	Dairy/beef	DNK	124.0				
Hege et al. (2003)	33	Farm-gate	Dairy/beef	DEU	47.0	− 4.4	− 18.3		
Klem et al. (2007)	8	Farm-gate	Dairy/beef	DEU	66.4				
Løes and Øgaard (1997)	12	Farm-gate	Dairy/beef	NOR		44.0	156.2		
Løes and Øgaard (2001)	5	Farm-gate	Dairy/beef	NOR		3.8			
Nielsen and Kristensen (2005)	13	Farm-gate	Dairy/beef	DNK	106.0	6.0			
Nowak et al. (2013)	36	Farm-gate	Dairy/beef	FRA	55.5				
Nowak et al. (2013)	34	Farm-gate	Dairy/beef	FRA		0.0	− 1.9		
Padel et al. (2013)	12	Farm-gate	Dairy/beef	AUT	101.0	0.8	8.3		
Padel et al. (2013)	5	Farm-gate	Dairy/beef	BEL	225.5	24.0	32.5		
Padel et al. (2013)	7	Farm-gate	Dairy/beef	DNK	80.3	− 3.0	1.5		
Padel et al. (2013)	7	Farm-gate	Dairy/beef	FIN	118.0	− 2.0	− 6.5		
Padel et al. (2013)	17	Farm-gate	Dairy/beef	GBR	119.8	45.3	2.8		
Padel et al. (2013)	7	Farm-gate	Dairy/beef	ITA	117.0	0.8	2.5		
Padel et al. (2013)	14	Farm-gate	Dairy/beef	ROU	80.5	4.3	9.0		
Ruane et al. (2013)	21	Farm-gate	Dairy/beef	IRL		9.4			
Starz et al. (2013)	10	Farm-gate	Dairy/beef	AUT	41.9	1.8	12.1		
Steinshamn et al. (2004)	1	Farm-gate	Dairy/beef	NOR	40.8	0.6			
Taube et al. (1997)	1	Farm-gate	Dairy/beef	DEU	110.0				
Watson and Atkinson (1999)	2	Farm-gate	Dairy/beef	GBR	157.5				
Wieser et al. (1996)	9	Farm-gate	Dairy/beef	DEU	− 7.7	0.8	4.2		
Bachinger and Stein-Bachinger (2000)	2	Farm-gate	Mixed	DEU	16.0				
Gutser et al. (2002)	9	Farm-gate	Mixed	DEU	35.2	− 6.6	− 10.7		
Hansen et al. (2000)	6	Farm-gate	Mixed	DNK	97.2				
Korsaeth (2012)	3	Farm-gate	Mixed	NOR	− 21.9	− 9.3	− 9.3		
Loges et al. (2006)	2	Farm-gate	Mixed	DEU	14.8				
Nesme et al. (2012)	23	Farm-gate	Mixed	FRA		10.3			
Nolte and Werner (1994)	1	Farm-gate	Mixed	DEU	11.0	− 2.9	− 65.0	− 8.4	
Oelofse et al. (unpublished data)	10	Farm-gate	Mixed	CHE	57.6	0.2	− 1.4		
Oelofse et al. (unpublished data)	7	Farm-gate	Mixed	DNK	35.2	12.2	24.8		

Table 1 (continued)

Study	N	Farm type	Budget kind	Country	N	P	K	Mg	S
Oelofse et al. (unpublished data)	11	Farm-gate	Mixed	EST	24.6	− 2.7	− 2.9		
Oelofse et al. (unpublished data)	8	Farm-gate	Mixed	GBR	22.9	− 2.9	− 2.2		
Oelofse et al. (unpublished data)	10	Farm-gate	Mixed	HUN	16.2	− 3.0	− 3.1		
Oelofse et al. (unpublished data)	5	Farm-gate	Mixed	ITA	35.3	10.7	6.6		
Goulding et al. (2000)	1	Farm-gate	Vegetable	GBR	96.0	1.9	− 20.0		
Zikeli et al. (2017)	22	Farm-gate	Vegetable	DEU	196.8	48.0	− 143.2	70.7	119.0
Andrist-Rangel et al. (2007)	3	Soil surface	Arable	SWE			− 44.9		
Asdal and Bakken (1999)	29	Soil surface	Arable	NOR	30.1	7.1	− 72.7		
Asdal and Bakken (1999)	30	Soil surface	Arable	NOR	21.6	− 5.2	− 60.0		
Boldrini et al. (2007)	6	Soil surface	Arable	ITA	246.0				
Erhart et al. (2002)	1	Soil surface	Arable	AUT	40.2	− 7.9	4.8		
Fliessbach et al. (2000)	2	Soil surface	Arable	CHE	− 175.0	− 5.5	− 27.0	5.5	
Haraldsen et al. (1999)	3	Soil surface	Arable	NOR	17.3	− 1.0	− 67.3		
Hartl and Erhart (2002)	1	Soil surface	Arable	AUT	40.3	− 8.0	4.7		
Migliorini et al. (2014)	2	Soil surface	Arable	ITA	− 10.7				
Möller (2009b)	8	Soil surface	Arable	DEU	58.1				
Morari et al. (2012)	2	Soil surface	Arable	ITA	49.1				
Oehl et al. (2002)	6	Soil surface	Arable	CHE		− 6.7			
Tagmann et al. (2001)	2	Soil surface	Arable	CHE		6.7			
Thorup-Kristensen et al. (2012)	3	Soil surface	Arable	DNK	− 31.7	− 12.0	− 56.0		
Torstensson et al. (2006)	2	Soil surface	Arable	SWE	− 11.0	− 8.5	− 19.0		
Bengtsson et al. (2003)	1	Soil surface	Dairy/beef	SWE		− 0.5	− 23.5	39.3	
Øgaard and Hansen (2010)	28	Soil surface	Dairy/beef	NOR			− 51.5		
Anglade et al. (2015)	68	Soil surface	Mixed	FRA	38.0				
Askegaard and Eriksen (2000)	4	Soil surface	Mixed	DNK			5.3		
Berry et al. (2003)	9	Soil surface	Mixed	GBR	23.2	8.2	− 11.7		
Foissy et al. (2013)	28	Soil surface	Mixed	FRA	− 6.0	− 1.4	− 15.0		
Gutser et al. (2002)	9	Soil surface	Mixed	DEU	7.6	− 7.4	− 16.2		
HungChun et al. (2016)	3	Soil surface	Mixed	DEU	25.7				
Korsaeth and Eltun (2000)	2	Soil surface	Mixed	NOR	− 43.6				
Schmidtke et al. (in press)	32	Soil surface	Mixed	DEU	− 11.0	− 9.0	− 38.9	11.8	
Erhart et al. (2002)	1	Soil surface	Vegetable	AUT	70.7	− 12.4	27.2		

The budgets not only differed between farm type and budgeting method, but there were also different amounts of studies and investigated farms for each subset (Fig. 1 and Supplementary Table 1). Most studies use the farm-gate method to calculate the budget. Especially for N, the difference between numbers of studies based on farm-gate ($n = 30$) and soil surface ($n = 19$) budgets was high. For K, the amount of investigated farms by farm-gate balances was double as the number of farms analyzed by soil surface studies. The study and farm count also differed among farm types. Most studies examined dairy/beef farms, closely followed by arable farms and mixed farms. Yet, there are noticeably lower amounts of studies done on vegetable farms. Further, the soil surface budget method was mostly used for arable and mixed farms, and almost all dairy/beef farms were examined using the farm-gate budget method.

The literature research yielded studies investigating farms from 15 different countries. The number of studies and farms differed highly. Most studies investigated German farms, followed by studies from Great Britain, Denmark, Norway, and Austria (Fig. 2, Supplementary

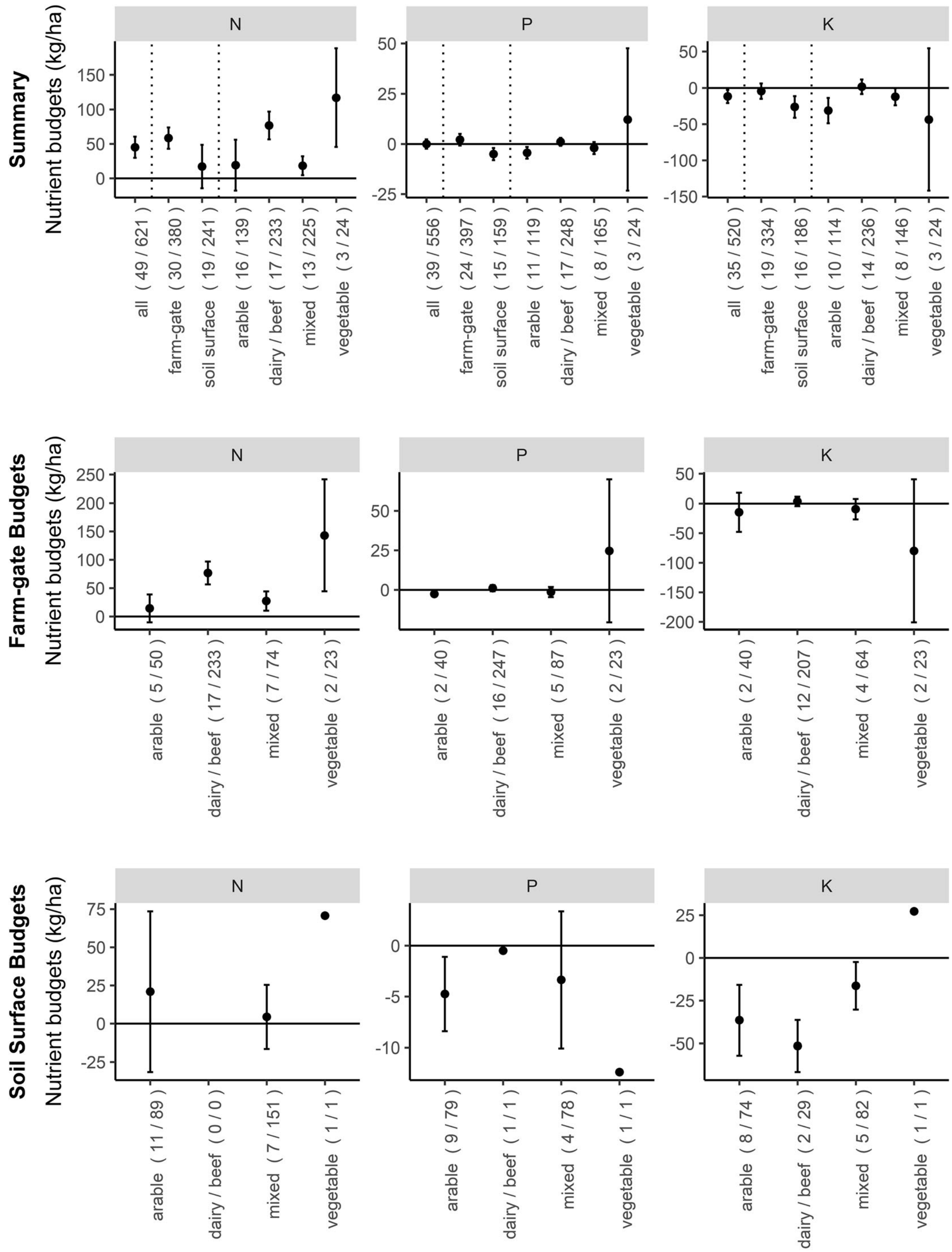

Fig. 1 Summary of the meta-analysis results of N, P, and K budgets as overall averages (top row), farm-gate budgets (middle row), and soil surface studies (bottom row). Dots represent the means derived from the meta-analysis in kg ha^{-1} $year^{-1}$ and the bars the 95% confidence interval. The numbers behind the labels on the x-axis show the number of studies and investigated farms

Table 1). Although only very few studies have been conducted in France, the number of farms investigated was high.

Difference between countries were observed for all nutrients (Fig. 2). A Belgian study by Padel et al. (2013) showed particularly high surpluses for N, P, and K. Also

Table 2 Results of the moderator test of the meta-analysis of N, P, and K budgets. Shown are the QM value and the p value of the moderator omnibus test as well as the R^2 as a measure of the explained heterogeneity for the moderators "farm type," "budget method," and a "dummy variable" consisting of both farm type and budget method

	Farm type		Kind of balance		Both (dummy variable)	
	p value	R^2 (%)	p value	R^2 (%)	p value	R^2 (%)
N	< 0.0001	26	0.0072	11	0.0006	24
P	0.0527	6	0.0051	17	0.0012	30
K	0.0123	14	0.0191	10	0.0003	31

the other countries investigated only by Padel et al. (2013), such as Finland or Romania, showed rather high budgets. Contrastingly, small budgets were observed in Sweden. However, the compositions of farm types investigated and budget method used differed significantly between countries. The investigated countries with number of country and farms for each farm type and budget method are shown in Supplementary Table 1.

Discussion

We observed a general imbalance in the nutrient supply of organic farms in Europe, where, as an average of the entire sector N, S, and Mg are supplied in excess of nutrient removal, the P budget is rather balanced due to high excesses in vegetable farms, and a removal of K in excess of resupply. In contrast to N and S, the effects of budget surpluses or deficits on plant supply of P, K, and Mg are based on long-term soil processes; a deficit might not cause immediate yield depressions primarily (Løes and Øgaard 2001; Cooper et al. 2018). Yet, the resupply of depleted soil reserves is a challenge. In order to avoid long-term soil depletion, the calculation of nutrient budgets enables the early identification of these deficits, allowing the implementation of measures that prevent gradual soil nutrient depletion, which is particularly important for organic farms as an undetected deficit of P, K, or S may result in a decrease of BNF (Römer and Lehne 2004; Scherer 2008).

In addition, it must be noted that balanced nutrient budgets do not necessarily indicate that nutrient management strategies are successful. As both farm-gate and soil surface budgets are often based on simple input/output calculations that disregard nutrient losses, these hidden deficits falsely shift nutrient balances towards the positive side. Especially N and S are prone to get lost from the system through, e.g., leaching or volatilization (Eriksen and Askegaard 2000; Berry et al. 2003). Therefore, certain surpluses in the amount of the unavoidable losses are needed to ensure adequate plant supply with N and S. This means organic farming systems can still be regarded as N limited systems even if the input/output budgets for N are positive.

The imbalances among the different nutrients arise either from the lack of use of fertilizers, but a high rate of leguminous crops in the crop rotation, meaning an input of N, but no inputs of mineral nutrients like P and K, or from the use of fertilizers that contain more than one nutrient but usually not in the same stoichiometry as the plant product offtakes. For example, solid manures or composts provide much more P in relation to the long-term offtakes by harvested products if they are applied in the needed amount of N (Möller and Schultheiß 2014). Therefore, the challenge for a suitable nutrient management system is to mix different fertilizers and BNF in a way that all nutrients are in a balanced input-output relation. In order to address these relations among nutrients, individual assessments for each farm are needed.

The represented means derived from the meta-analyses show the averages over all studies. The results of this study, however, highlight that in order to evaluate the nutrient budgets of organic farms, it is necessary to go into more detail since nutrient budgets differ depending on farm type, budgeting method, and country.

The number of studies reporting N, P, K, Mg, or S budgets also differed considerably. Research has been mainly focused on N, as it is the plant nutrient with the quickest effect on plant growth and yield (Röös et al. 2018), while the effects of imbalances for example of P and K can only be observed on a medium or long-term time span. Based on the current literature review, there is a need for more studies on Mg and especially S.

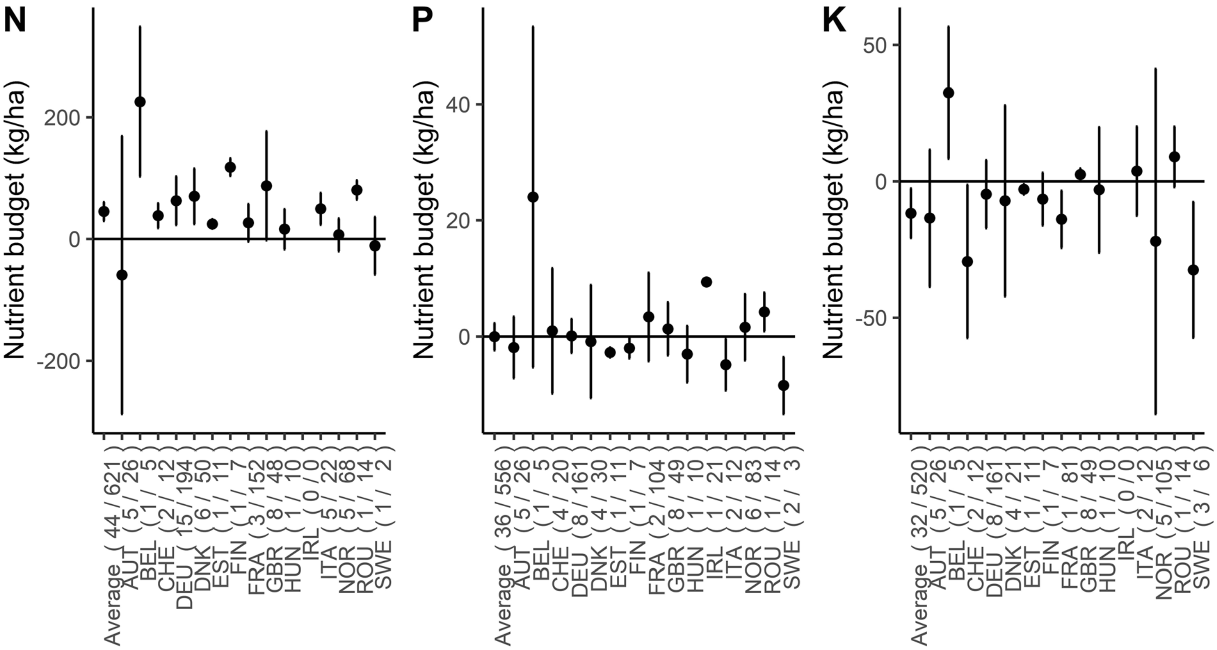

Fig. 2 Meta-analysis results of nutrient budgets of N, P, and K by country of origin. Dots represent the means derived from the meta-analysis in kg ha^{-1} $year^{-1}$ and the bars the 95% confidence interval. The number behind the labels on the x-axis shows the number of studies and investigated farms

In our study, farm type was the most important moderator of the N budgets ($R^2 = 26\%$). Arable and mixed farms showed lower overall nutrient balances compared to dairy/beef farms or even vegetable farms. For K and especially for P, farm type was of less importance in affecting heterogeneity of estimates ($R^2 = 16\%$ for K, $R^2 = 6\%$ for P). In practice, farm type specific averages instead of the overall averages must be used for the evaluation of nutrient supply for the organic sector to avoid misinterpretation of the results. Vegetable farms, for instance, showed high surpluses of P but only represent a small fraction of the overall organic farmed area. In contrast, arable and mixed farms showed negative P budgets while constituting the major share of the total organic area. The average of these farms may therefore not be extrapolated to the organic farming sector as a whole. In sum, the findings for N and P are in line with a review by Watson et al. (2002b), while they differ slightly for K. In contrast to our results, the authors found high K surpluses in vegetable and arable farms, small surpluses for dairy/beef farms, and slight deficits for mixed farms. However, their review focused more on dairy farms and showed only a small number of investigated arable, mixed, and vegetable farms. The difference among farm types can be explained by different nutrient management strategies.

In dairy farms, leys and forage legumes are a major tool for building soil fertility and adding N to the system through BNF. Further nutrient inputs derive from feed imports. Additionally, nutrients within farms can be recycled through animal manure production (Watson et al. 2002a). This use of animal manure, though, is always coupled with unavoidable losses, such as volatile N losses during storage and application (Taube and Pötsch 2001). These losses are not always included within N budgets as an output, therefore resulting in more positive budgets.

On arable farms, there is no possibility of nutrient recycling within the farm through manure and the amount of land devoted to leys and forage legumes is economically limited as no direct monetary return is achieved (Watson et al. 2002a). Therefore, soil fertility building is based on green manures, crop residue management, and grain legumes. Yet, these measurements usually do not fulfill the nutrient needs for other nutrients than N, and additional nutrient inputs must come from external fertilizers, such as compost or manures, in order to replenish nutrient exports. The amount of N import into the farm and the type of fertilizer that are permitted to be used in organic farming systems are limited, which often results in their low availability on the market. Especially for P, adequate fertilizers besides compost and manures are missing. Farmers, therefore, cannot use the amount of fertilizers they need, which results in lower nutrient budgets.

Mixed farms represent a mixture between the two former mentioned systems, with the production of cash crops, as well as animal products. These farms have nutrient inputs via leys or forage legumes incorporated in the rotation, sometimes also via feed import. The manure produced by the farms animals is mainly used for the fertilization of the cash crops. Therefore, a nutrient shift from permanent grasslands to the arable lands can often be observed (Möller 2009a). This results in an overall lower nutrient budgets, especially on a farm level.

Soil fertility building in vegetable farms differs significantly from the former mentioned systems. Production costs for indoor greenhouse production are so high that a crop rotation with green manures or leys is not economically feasible. In open field vegetable production, the N demand of several crops, especially of the *Brassica* sp., is so high that N should be supplied also by external N fertilizers with a high short-term N release. Therefore, vegetable farms rely to a high extent on external nutrient imports, such as compost, animal manure, or commercial organic fertilizers (Watson et al. 2002a; Tittarelli et al. 2017; Zikeli et al. 2017; Möller 2018). In comparison with the average vegetable biomass, compost or solid animal manures provide related to plant offtakes and accounting also for long-term nutrient release two to three times more P per unit N, which results in an P surplus, while K is often deficient (Zikeli et al. 2017).

Besides farm type, the method of nutrient budget calculation also moderated the magnitude of the nutrient budgets ($R^2 = 11\%$ for N, $R^2 = 17\%$ for P, $R^2 = 10\%$ for K). Farm-gate budgets showed in general higher budgets than soil surface budgets. The literature review revealed no study comparing these different budget methods. Higher farm-gate budgets in comparison to soil surface budgets suggest that even if farms are better supplied with nutrients, crop requirements on the field might not be as high. Since farm-gate studies are often used by policy makers (Watson et al. 2002b), it is important to emphasize that a high farm-gate nutrient surplus does not necessarily imply a high nutrient surplus on the field. The difference in nutrients might be explained by unaccounted storage losses of fertilizers, especially for nutrients prone to volatile losses such as N or S, and harvested products in the farm-gate budget calculation. In our study, the difference between soil surface studies and farm-gate studies might also lie in the composition of farm types for each budget method. Soil surface studies are usually carried out for arable farms, but not for dairy farms, which, as mentioned above, have higher budgets than arable farms. If the budgeting methods for each farm type are compared to each other, the difference among them was smaller. However, to allow a direct comparison, different methods of budget calculation need to be carried out for the same farm type.

The comparison among countries of origin for reported nutrient budgets should be interpreted with caution. The amount of research carried out in the reviewed countries differs significantly and the direct comparison might be biased due to different investigated farm types and budget methods. However, we observed some differences between countries (Fig. 2). Countries located in Central Europe such as Great Britain, Germany, and Denmark seemingly had higher budgets than more northern countries such as Sweden and Norway. A reason for these differences among countries could be farming intensity or availability of fertilizers permitted in organic farming. However, there is a clear need for a systematic study comparing nutrient budgets of organic farms throughout Europe simultaneously, using standardized method and distribution of farm types. The literature research only revealed two studies by Oelofse et al. (unpublished) on mixed and arable farms and Padel et al. (2013) on dairy farms, which compared differences among countries directly. Both studies cover seven different countries and compare budgets for N, P, and K.

Besides the poor coverage of countries, the studies also revealed additional limitations. Direct comparison among studies was often complicated due to differences in included inputs, outputs, nutrient losses, or differences in calculation of BNF. In the present study, we tried to account for these differences by including a high number of studies, which would allow for an accurate estimation of average nutrient budgets. The nutrient budgets have further uncertainties due to the assumption of standard values for nutrient contents and mistakes in the farmers bookkeeping (Zikeli et al. 2017), as well as high degrees of uncertainties in the calculation of BNF. BNF is highly dependent on environmental factors such as soil moisture or soil N content, and yield level (Anglade et al. 2015), which are usually disregarded in the calculations for budget studies.

In order to determine the severity of nutrient surpluses or deficits and to allow recommendations for action to farmers or even policy makers, soil data on nutrient contents is needed (Watson et al. 2002b). If soil nutrient contents are high, a negative budget might even be desired to avoid negative effects on the environment. In contrast, if soil nutrient contents are already low, nutrient deficits should be minimized in order to avoid soil depletion of these nutrients. Slight nutrient surpluses are then desired to increase soil nutrient level back to the optimal range for plant production (Korsaeth 2012). This is especially true for P, K, and Mg, since these nutrients are less mobile in the soil, which can therefore act as nutrient storage. Further, studies have shown that the soil content of plant available P and K is positively correlated with the budget (Reimer et al. under review; Løes and Øgaard 2001). Yet, only few studies include soil data. In the future, nutrient budget studies should aim to always incorporate soil data.

Finally, the topic of selection bias must also be addressed. Due to the language requirement, many studies had to be discarded. It seems that many nutrient budget studies are not always published in English, but rather in the language of the country of origin. This makes the studies more available to farmers within the country but not for international comparisons. Since the language requirement was extended to German, German speaking studies might be overrepresented in this study.

Conclusion

Nutrient budgets are a widespread tool in organic farming to investigate the nutrient supply of a farm. Most published studies in the presented meta-analysis investigate N, P, or K, while studies concerning Mg and S are rare. On average, over all farm types and budgeting methods, we observed a meta-analytical surplus of 45 kg N ha^{-1} year^{-1}, a balanced P budget of 0 kg P ha^{-1} year^{-1}, and a deficit of − 12 kg K ha^{-1} year^{-1}. Nutrient surpluses were also found for Mg (16 kg Mg ha^{-1} year^{-1}) and S (45 kg S ha^{-1} year^{-1}), although these should be interpreted with caution due to the low number of studies. However, the presented data does not provide an overall budget for the organic sector, as farms with deficits were underrepresented in the published literature, while specialty farms with high surpluses but a low area ratio (e.g., vegetable farms) were overrepresented. The type of farm represents an important factor, which should be considered when evaluating nutrient budgets of organic farms. In the current review, arable and mixed farms face more severe nutrient shortages than dairy/beef farms, while vegetable farms often have problems with nutrient surpluses. These imbalances between nutrients and farm types emphasize the challenge of nutrient management in organic farming by combining suitable fertilizers in a way that they match the composition of the farm's demand. Low availability of permitted fertilizers and the lack of adequate fertilizers, especially for P, complicate the achievement of this goal even further. To develop suitable nutrient supply strategies for organic farms throughout Europe, the actual nutrient demand of organic farms must be assessed with regard to geographical location, budgeting method, and farm type. At the moment, there is a clear need for studies which compare nutrient budgets from different countries with the same budgeting method and simultaneously take different farm types into account.

Authors' 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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Data availability The data set and the R script are available in the supplementary material.

Compliance with ethical standards

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

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