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ORIGINAL ARTICLE

Fertilisation strategies and their influence on nutrient flows in organic apple orchards

Birgit Lepp · Sabine Zikeli · Jens Hartung · Kurt Möller

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Abstract In organic fruit production, permitted fertilisers contain multiple nutrients with stoichiometries differing from the nutrient offtakes of the fruit trees. Furthermore, some pesticides contain nutrients resulting in additional inputs. These conditions may cause unbalanced nutrient supplies and thereby influence the long-term sustainability of the system. An analysis of nutrient management practices in organic apple farms was conducted in three Southern and one Northern German apple-growing region. Data on nutrient inputs (via fertilisers and pesticides) and outputs (via fruit) per orchard were collected along with soil samples from up to five orchards per farm on 19 farms. On average, farmers fertilised 37 kg N and harvested 23 Mg apples per ha and year. Nutrient budgets showed imbalances for N (+25 kg ha^{-1} $year^{-1}$), P (+3 kg), K (−4 kg), Ca (+37 kg), Mg (+4 kg), S (+53 kg), Na (+4 kg) and Cl (+3 kg). Base fertilisers like compost or manure contributed to higher nutrient inputs due to a larger P and K-to-N-ratio. Commercial organic fertilisers such as keratins or vinasse contained much lower ratios. The main S input sources were pesticides (46 kg). N inputs by base ($p = 0.06$) and commercial ($p = 0.37$) fertilisers had no significant effect on the yield. Balanced nutrition can best be achieved by applying a combination of 20% of the total N demand via base fertilisers, complemented with commercial fertilisers with low element-to-N-ratios (e. g. keratin fertilisers, vinasse or biological N_2 fixation). No correlation was found between soil nutrient status and nutrient budgets. Site conditions and internal field nutrient flows (transfer of the inter-row biomass via mulching into the tree row) had a stronger influence on the soil nutrient content than fertilisation strategy. In addition, fruit orchards showed a spatial differentiation of soil nutrient contents. Elevated P and K contents above the recommended range in the tree row were found in 67% of the orchards, while tendencies of depletion were found in the inter-row area. Mulching schemes which transfer biomass from the inter-row area to the tree row need to be adapted to this condition.

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B. Lepp (✉) · K. Möller
Institute of Crop Science, Fertilisation and Soil Matter Dynamics, University of Hohenheim, Fruwirthstr. 20, 70599 Stuttgart, Germany
e-mail: birgit.lepp@uni-hohenheim.de

S. Zikeli
Centre for Organic Farming, University of Hohenheim, Fruwirthstr. 14-16, 70599 Stuttgart, Germany

J. Hartung
Institute of Crop Science, Biostatistics, University of Hohenheim, Fruwirthstr. 23, 70599 Stuttgart, Germany

K. Möller
Centre for Agricultural Technology Augustenberg, Institute of Applied Crop Science, Kutschenweg 20, 76287 Rheinstetten, Germany

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Introduction

Apples are the most important fruit crop in Germany and organic apples are a key product for organic consumers. Currently, around 1 Mio Mg of apples are produced per year on 33,000 ha with an average yield of 30 Mg ha^{-1}. Of these, 8,000 ha are under organic management, with a yield of around 20 Mg ha^{-1} per ha (Destatis 2024). In organic production, one of the objectives is maintaining the long-term soil fertility (European Union 2018). To achieve this, neither nutrient depletion nor excessive nutrient supply resulting in nutrient losses e.g. through leaching should be aimed for, but rather a nutrient efficient management with a balanced nutrient input and output. This challenges the sustainability of fertilisation in organic fruit orchards: Fertilisation strategies in organic farming are based on a mixed farming concept with animal husbandry that strongly focuses on internal nutrient recycling. With perennial crops like apples, nutrient management challenges arise since it is difficult to apply organic principles that were designed for mixed farming systems: orchards are usually cultivated for about 25 years or longer as a monocrop. Therefore, crop rotation for pest and disease control and the use of legumes for N_2 fixation are difficult to apply. Since legumes are not usually grown as a main crop in apple orchards, a key component in the organic farming nutrient supply systems is missing. Furthermore, fruit farms are highly specialized farming systems, very often without any kind of animal husbandry, which means they usually do not have access to internal nutrient sources such as farmyard manure or slurry. This situation results in dependence on external inputs. To ensure an adequate nutrient supply, numerous fertilisers permitted in organic farming are available. These include bulky, relatively cheap "base organic fertilisers" such as manure or compost, or more expensive "commercial organic fertilisers" such as keratins (horn products, feather meal, hair meal, wool), vinasse from sugar production, or other residues of the food or feed production industry.

In contrast with legumes, which only introduce nitrogen into the system, all permitted base and commercial fertilisers are multi-element fertilisers. Depending on the type of fertiliser, they can contain a high proportion of phosphorus (P, e.g., manures from pig or poultry husbandry, compost, meat and bone meal), calcium (Ca, e.g., manure, compost, meat and bone meal), potassium (K, e.g., dairy manure, vinasse) or sulphur (S, e.g., keratins, vinasse) (Möller and Schultheiß 2014). Generally, the nutrient stoichiometry of most commonly used fertilisers does not match those of the harvested products (Möller 2018; Möller and Schultheiß 2014). In addition, in organic fruit growing pesticides that may also contain nutrients like K, Ca and S are used to control fungal pathogens. Application of such pesticides result in further nutrient inputs that are usually not accounted for in calculations on fertiliser inputs. Consequently, an imbalanced nutrient supply can be assumed for organic fruit orchards, resulting in an accumulation or depletion of nutrients in the soil. A nutrient deficiency in the soil can have direct negative consequences (e.g., on fruit quality by K deficiency, Hunsche et al. 2003). In the long-term imbalances threaten the sustainability of the system. Moreover, fertilisers of conventional origin are considered contentious inputs, and there are tendencies within some organic growers organizations to phase them out from use in organic agriculture (Oelofse et al. 2013; Demeter e.V. 2023).

In the literature there is limited data indicating nutrient imbalances in organic cropping systems (Zikeli et al. 2017; Möller 2018 and references therein; Reimer et al. 2020a, b). To our knowledge, there is only one other published study dedicated to nutrient flows in organic orchards: Alber et al. (2018). Therefore, there is a lack of data providing an overview of the current situation. The present study investigates current fertilisation strategies and nutrient budgets in organic apple production. This information can serve as a basis to develop strategies to improve overall soil fertility management. In detail, the following research questions are addressed:

A) Which fertilisers are used and what are the overall nutrient inputs?
B) How large are the nutrient outputs and to what extent do nutrient imbalances exist?
C) Which management practices (fertilisation strategies / plant protection strategies / management

of the inter-row area) influence orchard nutrient budgets most?

D) Is there a relationship between nutrient budget and nutrient content in the soil?
E) What are the main drivers determining soil nutrient and organic matter content?
F) To what extent does the soil nutrient content differ between the tree row and the inter-row area?
G) What are the main factors that influence apple orchard productivity?

To address these research questions nutrient monitoring was conducted to gather data on current nutrient management practices in organically farmed orchards in Germany's primary apple-growing regions (Baden Württemberg and the region Altes Land (Hamburg and Lower Saxony)). Nutrient budgets for selected orchards were calculated based on a semi-structured questionnaire. Survey data were supplemented by soil samples from the corresponding orchards to relate the results of the nutrient budgets to soil nutrient concentrations.

Materials and methods

Surveys

A survey was carried out in four different apple growing regions within Germany. To contact farmers for participation in the survey, a project description and a request to participate in the survey was sent by the German farmer's Association for Organic Fruit Growing (Fördergemeinschaft ökologischer Obstbau e.V., FÖKO e.V.) to their members. To receive a larger sample size, some farmers were contacted directly by local advisors and by representatives of the farmers' organization. The sample of organic apple producers covered various management approaches in the main apple growing regions in Germany. However, the farms were not selected randomly, and therefore should not be considered as representative for the entire sector for several reasons. For example, only farmers with appropriate documentation of management practices could be included. Furthermore, we assume that mainly farmers with a high awareness concerning soil health and fertilisation management were willing to participate in our survey. Altogether, 19 organic apple growers were interviewed across the different regions. In south Germany, semi-structured interviews were completed in 2016 on four farms in the Stuttgart-Heilbronn area ("Neckar"), five farms in the Lake Constance area ("Constance") and six farms in South Baden ("Freiburg") to cover the main fruit growing regions of Southern Germany (Supplementary Fig. 1). For the Northern-German region "Altes Land", farms were contacted in 2019 and four farmers participated (Supplementary Fig. 1). Regional soil types can be found in Supplementary Table 1.

The interview focused on general fertilisation strategies, and data on fertilisation and crop protection as well as on yields were collected. Up to five orchards per farm (a unit of trees with same variety, age and management), bearing full yield, were then selected for field budget calculation and soil sampling, resulting in 64 sites in total. The orchards averaged 1.3 ha in size, with a maximum of 4.6 ha. Most of the orchards were planted with trees grafted on M9 with a row spacing of 3–4 m and a planting distance of 0.5–1.5 m. Data were gathered retrospectively for 5 consecutive years: 2012–2016 for South Germany, 2014–2018 for Altes Land. Poseidon (a database and decision support tool, which documents inputs of fertilisers and pesticides and which is widely used by organic fruit farmers in Germany) was used in some cases to compile data on fertiliser application and use of pesticides. The farms differed in terms of length of organic management (between 43 and 3 years) and the selected orchards varied in apple variety, age of apple trees and the length of time used as a fruit orchard.

Soil sampling and analyses

In each orchard, 20 soil samples were taken with an auger to a depth of 0.3 m and then merged into one mixed sample (separately for the tree row and the inter-row area), as prescribed in the recommendations of the local extension service in Germany (LVWO 2021). The recommended sample depth was based on Paltineanu et al. (2017), who found the highest root density in intensive apple cultivation within a depth of around 0.3 m and a distance from the tree trunk of about 0.4 m. The samples were then air dried and sieved to 2 mm. Soil analysis was conducted for total carbon (C_t), soil organic matter content (C_{org}), N_t, S, extractable P, K and magnesium (Mg) and pH ($CaCl_2$); C_t, N_t and S_t concentrations were determined by combustion (Vario EL-CUBE Elementar Analysesysteme GmbH). For C_{org} analyses, carbonates were removed with hydrochloric acid, and then C was measured again with the elemental analyser. P and K were extracted at pH 3.6 with a calcium-acetate-lactate solution and then the concentration in the solution was determined photometrically (Flame emission spectrometer (K), spectral photometer (P); VDLUFA 2012). Mg was extracted in a solution of 0.0125 M $CaCl_2$ and determined through atomic absorption spectroscopy (AAnalyst 400 AA Spectrometer; VDLUFA 1991). The pH was measured in a 0.1 M $CaCl_2$ suspension (VDLUFA 2016).

Nutrient budget calculation

Input and output data from the 5 years were summed and the average was calculated. The nutrient budgets were calculated at field level for N, P, K, Ca, Mg, S, Na and Cl. Nutrient inputs included all fertilisers as well as pesticides containing these elements, mainly fungicides for control of *Venturia inaequalis* that contain S, K and Ca. If possible, farmers provided specific values for the N, P, and K contents of the fertilisers; missing values for certain elements were supplemented by using standard data from the literature (Möller and Schultheiß 2014) and product data sheets (data used for calculations is reported in Supplementary Table 2). Nitrogen inputs via biological N_2 fixation e.g., through the cultivation of leguminous mulches in the tree row as practiced by individual fruit growers were not considered. For pesticides, elemental contents were derived from the product data sheets. The nutrient output was calculated by multiplying the fruit yield by the nutrient concentration of apples (Souci et al. 2011; Möller and Schultheiß 2014).

For each orchard and each element, nutrient budgets were calculated as (Eq. 1):

$$B_{ij}\left[\text{kg ha}^{-1}\text{a}^{-1}\right] = IN_{ij} - OUT_{ij} \tag{1}$$

where B_{ij} is the yearly total nutrient budget of farm i and orchard j, IN_{ij} is the yearly nutrient input and OUT_{ij} is the yearly nutrient output of farm i and orchard j. The nutrient output is considered as the nutrient content of the harvested apples.

The yearly total nutrient input for each nutrient was calculated as (Eq. 2):

$$IN_{ij}\left[\text{kg ha}^{-1}\text{a}^{-1}\right] = CF_{ij} + CP_{ij} \tag{2}$$

where CF_{ij} and CP_{ij} are the nutrient content of the fertilisers and pesticides used at farm i and orchard j per year, respectively.

Nitrogen use efficiencies (NUE) were estimated as the slopes of the multiple regression of N output on N inputs that are based on base fertilisers and commercial fertilisers.

Liming effect

The liming effect of the fertilisers used was calculated according to the Pierre-Sluijsmans equation (modified after Harmsen et al. 1990) (Eq. 3):

$$\begin{aligned} E_{ij}\left(\text{kg}CaOha^{-1}\right) = {} & 1.0CaO_{ij} + 1.4MgO_{ij} + 0.6K_2O_{ij} + 0.9Na_2O_{ij} \\ & - 0.4P_2O_{5_{ij}} - 0.7SO_{3ij} - 0.8Cl_{ij} - nN_{ij} \end{aligned} \tag{3}$$

where E_{ij} indicates the liming effect of farm i and orchard j caused by 100 kg of applied fertiliser on the soil, calculated in kg CaO ha^{-1}.

The nutrients in the fertilisers are expressed as proportions of the fresh matter (w/w). The dimensionless coefficient n is needed to assess the acidifying effect of N derived from fertilisers. Theoretically, values for n are in the range of 0–2. In our calculations, a coefficient of 1 was used. A positive value of E_{ij} shows a net liming effect of the fertiliser, while a negative value shows the net lime requirement to compensate for the acidifying effect of the overall management.

Statistical analysis

For the response variables pH, C_{org} and nutrient concentrations in the soil a model selection was performed using the Akaike Information Criterion (AIC; Wolfinger 1993) as the selection criterion and all subset methods as the selection method. The model with the smallest AIC was considered the best fitting model. The predictive variables that were tested were affiliation to a farmers' association, region, soil texture, pH-value of the soil, soil organic carbon, years of organic management, age of apple trees, nutrient budget, ratio of total N input applied through base fertilisers, N input through base fertilisers and N input through commercial fertilisers. For yield the apple variety, soil N, P and K content and P, K and

S input were added as predictive variables instead of farmers' association and nutrient budget. As some of the variables were considered as fixed effects, the maximum likelihood estimation method was used for model selection via AIC. Additionally, a random farm effect was fitted. This effect accounts for the stratified structure of the survey data. The final model was refitted using a restricted maximum likelihood algorithm (REML; Patterson and Thompson 1971) and Wald-tests ($\alpha = 0.05$) were performed for selected factors. Normal distribution and homogeneous variances of residuals were checked graphically. If necessary, data were transformed logarithmically and the selection was redone. For significant factors ($p < 0.05$) in the final model, an LSD test was performed and results of multiple comparisons were presented as a letter display (Piepho 2012). For other fixed effects, slope values were estimated.

Additionally, means were calculated for the following variables: For means of yearly nutrient field budgets across farms, the model was simplified by dropping all fixed effects. Thus, the model included a general intercept and a random farm effect. For soil extractable P, K, and Mg concentrations and soil pH in the orchards, means per region were calculated by fitting a model dropping all fixed effects except region. Again, a random farm effect remained in the model. The latter resulted in a weighted least square estimate for traits of interest.

Results

Surveys

All farmers used commercial fertilisers, except two, who did not fertilise the orchards at all (one farm from "Freiburg" and one from "Altes Land"). Most common products were vinasse (nine farmers), Bioilsa (pellets containing feather meal, plant-based press cakes and vinasse; seven farmers), hair meal pellets (pig bristles, six farmers) and legume seed grit (four farmers). Farmers of all four regions used vinasse, while "Bioilsa" was only applied in the three Southern regions, hair meal pellets in "Altes Land", "Constance" and "Freiburg", peas and faba beans only in "Freiburg" and "Neckar". Additionally, nine of the farmers of all four regions used base fertilisers like compost, champost (residues of the substrate from mushroom production) and manure, four of these with amounts of more than 50% of the total fertilised N. The fertilisation level ranged from 0 to 93.1 kg N ha^{-1} per year, with an average of 36.8 kg N, and an average yield of 23.4 Mg fresh matter ha^{-1}.

Nutrient flows and field budgets

Base and commercial fertilisers vary in their nutrient concentration and nutrient stoichiometry. Base fertilisers generally have larger element-to-N-ratios compared with commercial fertilisers, especially for the ratios of Ca:N and Mg:N, but also P:N (Fig. 1). Vinasse in particular has some of the highest concentrations of K and Na of all fertilisers used. Animal waste products (especially keratins) have similar S:N ratios to manure and compost, but otherwise are very low in other nutrients.

The results of the field nutrient budgets of all fields on the 19 farms indicate surpluses for the elements N (25 kg ha^{-1} year^{-1}), P (3 kg ha^{-1}), Ca (37 kg ha^{-1}), Mg (4 kg ha^{-1}), S (53 kg ha^{-1}), Na (4 kg ha^{-1}) and Cl (3 kg ha^{-1}) (Fig. 2). A negative budget was calculated for K (-4 kg ha^{-1}). Commercial fertilisers had a higher influence on the N budget, while base fertilisers had a major impact on Ca and Mg inputs. Of all elements, P input was relatively evenly generated between base (2.5 kg ha^{-1}) and commercial (2.6 kg ha^{-1}) fertilisers. For K, the largest inputs came from base fertilisers (10.1 kg ha^{-1}), while the inputs from commercial fertilisers (6.6 kg ha^{-1}) and pesticides (6.4 kg ha^{-1}) were similar. The S inputs were mainly related to the use of pesticides (46 kg ha^{-1}, ranging from 3 to 93 kg ha^{-1}). Na inputs were generally caused by the use of manure and vinasse, Cl inputs by compost, champost and vinasse. The overall acidifying effect of the inputs was due to the pesticide input and, to a lesser extent, the application of some of the commercial organic fertilisers and the nutrient offtakes by fruits. Base fertilisers, on the other hand, contributed to a liming effect. On average, every farm applied 21.6% of the total N via base fertilisers. The higher the share of total N applied through base fertilisers, the higher the budgets across all considered nutrients with the exception of S (Fig. 3), while the lower the use of base fertilisers the lower the budgets for N, P, K, Mg and the lower the liming effect.

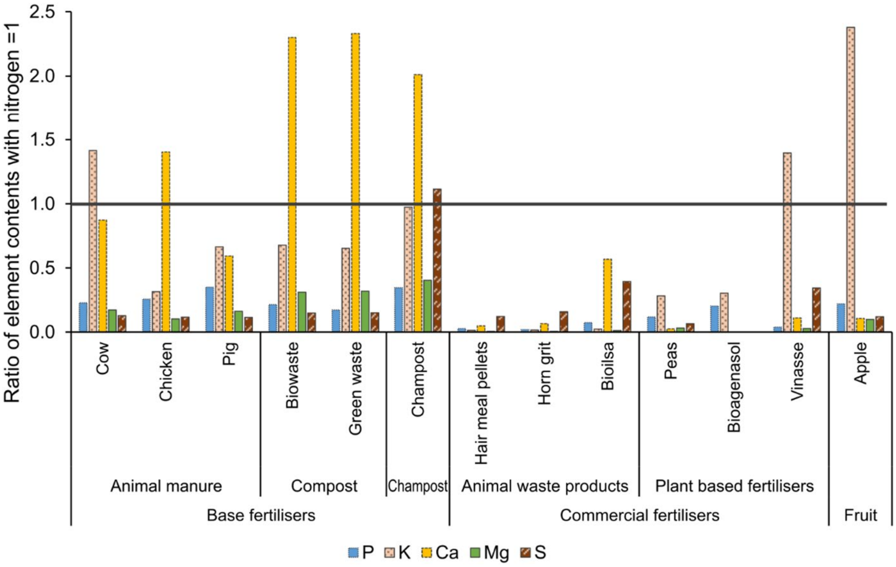

Fig. 1 Relative share of macro nutrients to nitrogen (= 1) in different fertilisers frequently used by fruit farmers in Germany, compared with nutrient levels in apples (based on Möller & Schultheiß 2014; Souci et al. 2011, and product data sheets). Values are shown as element to N ratio. The higher the values, the higher the supply of the element when applying an amount of fertiliser with a given N concentration

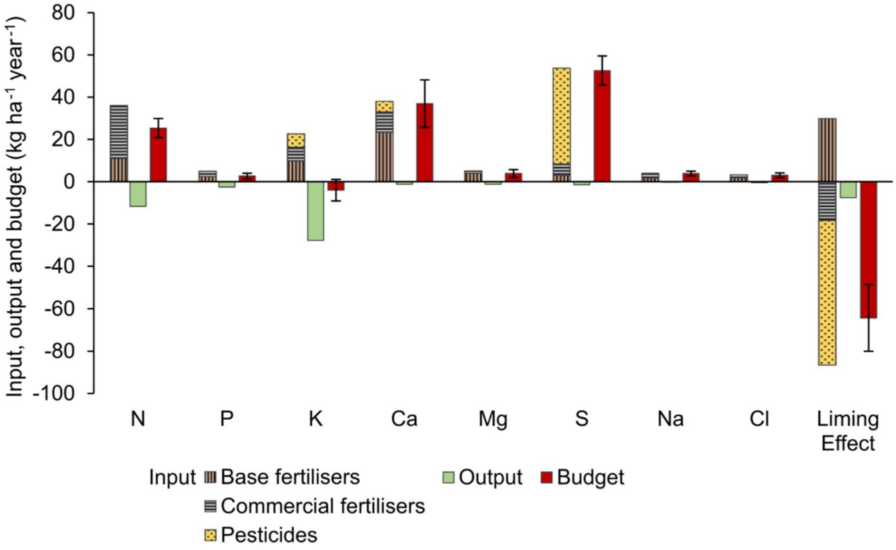

Fig. 2 Means of inputs, outputs and budgets (kg ha^{-1}) of all fields of the 19 fruit farms as a mean of 5 years ± standard error (SE)

Soil analysis

The soil textures in the orchards ranged from loamy soils in the Lake Constance region, to loamy (two thirds of fields sampled) and clayey soils (one third of fields sampled) in the Freiburg and Neckar region, to primarily clayey soils in the Altes Land region (Supplementary Table 1). Soil nutrient and C_{org} concentrations as well as soil pH varied significantly between regions: the pH was lowest in "Altes Land", followed by "Constance". C_{org} concentrations were highest in the Constance region. Soil extractable P and K (P_{CAL} and K_{CAL}) were highest in the Freiburg region, while Mg concentrations were highest in "Altes Land" (Table 1). In all regions mean values for extractable P, K and Mg in the tree row were significantly higher than the recommended range, according to the German classification of nutrient content in the soil as a base for fertiliser recommendations by VDLUFA (KTBL 2015; VDLUFA 2018). The minimum values were mostly still within the recommended range.

Soil extractable P, K and Mg were significantly higher in the tree row compared with the inter-row area. Also C_{org} levels were generally slightly higher

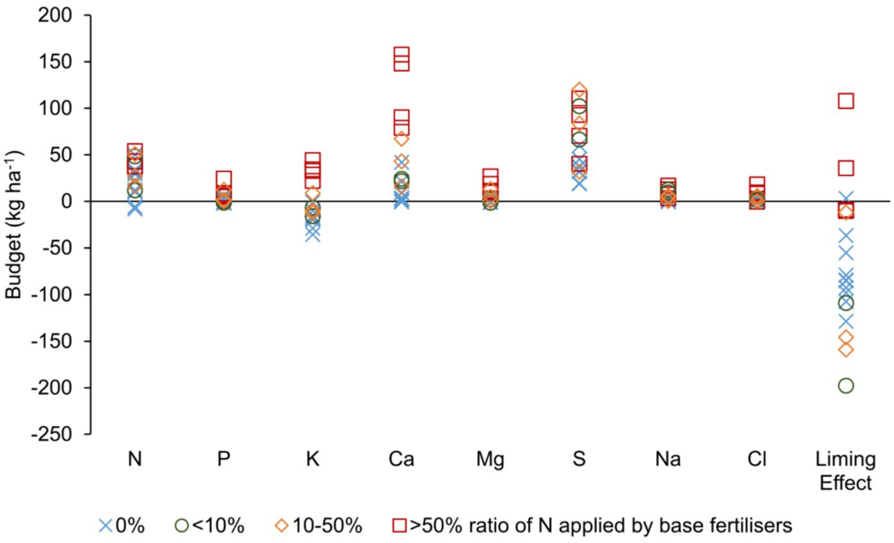

Fig. 3 Field nutrient budgets of 19 farms in Germany. Farms were categorised into four classes depending on the ratio of N applied via base fertilisers compared with total N applied (0, <10, 10–50, $>50\%$)

Table 1 Soil extractable phosphorus, potassium, and magnesium concentration, soil pH and organic carbon concentration in the orchards of the four German sampling regions (concentrations in the air-dried fine earth fraction)

Region	Orchards		P_{CAL} (mg/kg)		K_{CAL} (mg/kg)		Mg $CaCl_2$ (mg/kg)		pH $CaCl_2$		C_{org} (%)	
			Row	Inter-row	Row	Inter-row	Row	Inter-row	Row	Inter-row	Row	Inter-row
Constance	20	Mean	92	42	202	63	119	85	5.7	5.4	2.58	2.31
		Min	37	16	64	29	77	51	5.0	5.0	1.68	1.57
		Max	184	80	364	158	167	139	7.1	7.2	3.66	3.74
Freiburg	16	Mean	101	70	278	153	107	93	6.8	6.7	1.52	1.52
		Min	46	34	133	53	87	68	5.4	5.5	1.17	1.06
		Max	183	120	492	247	139	106	7.4	7.4	1.99	1.99
Neckar	12	Mean	103	72	269	177	174	167	7.0	6.9	1.73	1.63
		Min	26	15	111	79	95	93	5.4	5.5	1.12	1.12
		Max	246	238	415	352	293	309	7.3	7.3	2.25	2.39
Altes Land	16	Mean	88	49	250	123	214	207	5.6	5.7	2.32	2.00
		Min	38	18	132	60	151	147	4.6	4.7	1.60	1.75
		Max	183	107	488	168	316	303	6.7	6.9	3.27	2.38
All	64	Mean	97	59	253	131	143	128	6.3	6.3	1.95	1.82

in the tree row, while pH values were similar in the row and inter-row area. Approximately 73% of the samples in the tree row and 37% in the inter-row area showed P_{CAL} levels above the recommended range. K_{CAL} values were higher than recommended in 89% of the tree row soil samples, as well as 22% of the inter-row soils. 3% of the samples in the tree row as well as 18% in the inter-row area simultaneously showed P_{CAL} and K_{CAL} values in the optimal range (black box in Fig. 4). Furthermore, around 67% of the orchards simultaneously showed P and K values in the tree row above the recommended range (14% in the inter-row area); in 17% of the orchards the values were more than two times higher than recommended. P and K values in the inter-row area were in the optimum range or below in the majority of the orchards (Fig. 4). In only one orchard was the P concentration in the tree row lower than recommended, while in 23% of the inter-row areas it was lower than recommended. A similar pattern can be described for K, however the share of inter-row soils with K concentrations below the recommended range was

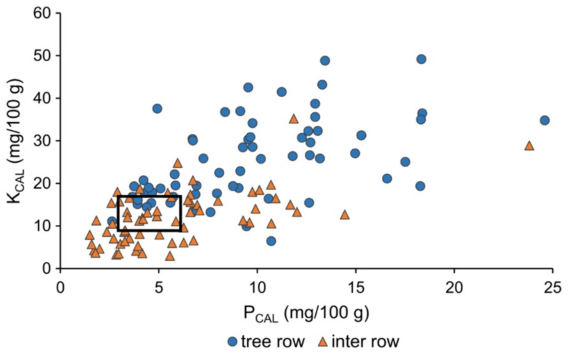

Fig. 4 Soil CAL-extractable phosphorus and potassium levels in the sampled apple orchards compared with the recommended range (according to VDLUFA (KTBL 2015; VDLUFA 2018) as black box. (Color figure online)

higher (38%) than for P. Regarding extractable Mg, the measured values were in the recommended range or above in the tree row as well as the inter-row area (data not shown).

A direct relationship between budgets and soil properties was not found for P, K, Mg, or for pH (Fig. 5). Adding further factors (site conditions, soil properties, fertilisation strategies; Table 2) potentially affecting the soil element concentration within a multiple regression approach did not alter results. The input of N through base or commercial organic fertilisers could only be linked to soil Mg, S concentration and pH, however, the only significant relation ($p < 0.05$) was observed between the ratio of total N applied through base fertilisers and the S content (Table 2). Total nutrient inputs via fertilisation, calculated in amounts of N, were not related to P, K, N or C_{org} levels in the soil.

Soil texture was related to soil K and Mg concentrations, as well as pH, with higher extractable K and Mg and lower pH in clayey soils. The affiliation to a farmers' association was significantly linked to soil P concentration. Soil extractable P, soil pH and C_{org} correlated with the number of years of organic management. Soil S content and soil pH were significantly related to the age of the apple trees.

Apple orchard productivity

Regarding regional differences, the highest yields were achieved in the Neckar region (29.8 Mg ha^{-1}), followed by "Constance" (24.8 Mg ha^{-1}) and "Altes Land" (21.7 Mg ha^{-1}), while the lowest yields were obtained in "Freiburg" (18.6 Mg ha^{-1}). At the same time "Neckar" and "Altes Land" showed the highest nutrient inputs as well as nutrient budgets. The estimated NUE was 9.5% (95% confidence limit: 5%; 14%) for those farms that only used commercial fertilisers. For the farms also using base fertilisers NUE was 2.2% (95% confidence limit: −3%; 8%). This result means an increase in yield of 190 or 44 kg per kg N-input, respectively. A model selection was carried out, in order to identify factors which might

Fig. 5 Nutrient content and pH in the tree row depending on the nutrient budget and liming effect (64 orchards on 19 farms)

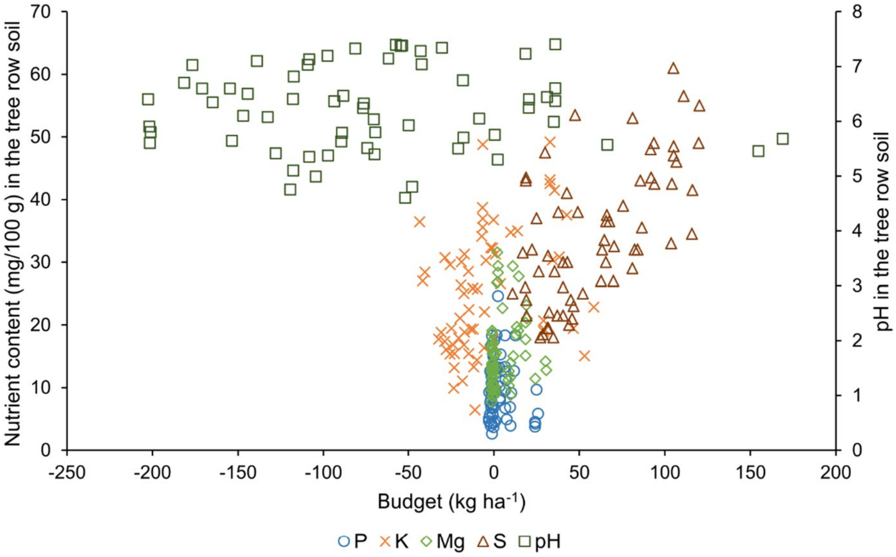

Table 2 Predictors on soil nutrients, C_{org} and pH were selected via AIC and all subset selection

Concentration in the soil	Site conditions					Tree row soil		Fertilisation			Budget	R^2
	Region	Farmers' association	Soil texture	Years of organic management	Age of apple trees	pH	C_{org}	Ratio of N by base fertilisers	N input by base fertilisers	N input by com. fertilisers	P, K, Mg, N, S, liming	
P (CAL)		0.046		**0.107**		**0.0031**						0.257
K (CAL)			0.022									0.071
Mg ($CaCl_2$)	0.0004		0.009				**0.1300**	**0.092**	0.148	**0.139**		0.503
N_t	0.0166	0.387			**0.656**	**0.0056**	**<0.0001**					0.797
S_t	<0.0001				**0.009**	**0.0003**	**<0.0001**	**0.001**		**0.059**		0.605
C_{org}	0.0001			**0.039**	**0.083**	**0.0070**	–				–	0.008
pH ($CaCl_2$)	<0.0001	0.405	0.129	0.081	0.004	–	**0.0170**	**0.178**	**0.174**	0.546	0.001	0.518

The presented *p*-values correspond to Wald tests of the corresponding factor or regressor

For all regressor variables: Values in bold indicate a positive slope. In case of logarithmic data transformation, a positive slope corresponds to a ratio larger than 1 and a negative slope corresponds to a ratio smaller than 1 on the original scale

Table 3 Factors influencing yield

Factors influencing the yield (kg ha^{-1}) model $R^2 = 0.618$	Slope	*p*-value
Region		0.001
Variety		0.004
Concentration in the tree row soil		
N (%)	−18,052	0.431
P (mg kg^{-1})	20	0.354
K (mg kg^{-1})	16	0.231
Nutrient input		
Ratio of N by base fertilisers (%)	−246	0.012
N input by base fertilisers (kg ha^{-1})	254	0.055
N input by commercial fertilisers (kg ha^{-1})	68	0.368
S input (kg ha^{-1})	99	0.069

potentially have an effect on yield and which could provide an explanation for the recorded yield differences (Table 3): In the selected model, region and apple variety significantly correlated with the yield ($p = 0.001$ and $p = 0.004$). Soil P and K concentrations were positively correlated with yield, while N concentration in the soil was negatively correlated but not statistically significant ($\alpha = 0.05$). While the relationship between yield and N input was positive, higher ratios of N applied via base fertilisers compared with total N input had a significant negative relationship to yield. Total S input was positively correlated with yield. No relationship was detected between yield and soil type, years of organic management, age of apple trees, soil pH, C_{org} content or P and K input.

Discussion

Orchard productivity and N fertiliser efficiency

In the present study regression analysis showed a weak but positive trend in yield with higher N input. This result indicates a very flat production function for fertilisers, and therefore a low dependency of overall productivity on fertiliser inputs. This finding is likely related to the fact that, in addition to the ratio of N applied by base fertilisers, region and variety had a significant influence on yield. Different climatic conditions lead to variances in vegetative growth and yield (Tustin et al. 1997). Hahn et al. (2023) found cultivar and weather conditions primarily determining yield, with no significant differences between fertilisation levels. In mature apple orchards it is possible to gain similar yields with and without fertilisation over years (Ristel and Clever 2016; Schunk et al. 2022), which means there is more or less no increase in yield per applied N-unit. A reason may be the sufficient nutrient concentrations in the two mentioned studies as well as in the investigated orchards here, paired with rather low nutrient outputs.

The low influence of overall fertilisation on yield was also supported by the data indicating a very low NUE. In perennial systems like apple orchards NUE cannot be compared with arable crops, since some of the N is used for stem and branch growth, and a large share of N from leaves are translocated to the stem in autumn, providing N for the next season. Therefore, the N uptake in 1 year not only affects the yield in that given year, but also influences tree performance in the following years. The higher N-efficiency of systems based on relatively quick-release organic commercial N-fertilisers compared with compost is consistent with other findings (Zikeli et al. 2017). The low NUE is due to the high C-N ratio in manures (10–24:1) and composts (16–20:1) (Möller and Schultheiß 2014) with a N availability in the year of application of 5–15% (Amlinger et al. 2003; Möller 2018), compared with the C-N ratio in hair meal pellets (4:1) and vinasse (7:1) (Möller and Schultheiß 2014). Even in the long-term, only smaller ratios of the compost-N will become plant available and will be finally taken up by plants compared with fertilisers with a narrower C-N ratio, due to losses through volatilisation, denitrification or leaching (Möller 2018). The lower N-availability of base fertilisers also explains why there is a negative effect on yield with higher shares of N applied by base fertilisers. When the same amount of N is applied, the trees have less N available to them when it is applied as a base fertiliser compared with application via commercial fertilisers.

The question remains whether fertilisation measures are worth the low increase in yield. Dierend et al. (2006) do not recommend relinquishing the use of fertilisers because, although mineralisation from the soil may be enough quantitatively, its timing may not be compatible with the demand of the trees, resulting in temporal N deficits. Secondly, since nutrients are stored in the tree biomass it seems that mature apple trees can compensate for a limited nutrient supply for years. However, in the first few years unfertilised young apple trees can exhibit significantly lower yields compared with fertilised trees (Kelderer et al. 2014). Just as excessive nutrient input and resulting losses due to leaching or runoff must be avoided, depleting the soil should not be the aim either. Even if there is no immediate effect, it may be detectable in the next generation of fruit trees that are established. Instead, the goal should be fertile soil with optimal nutrient storage and a nutrient management system that is balanced in the long-term with inputs and outputs nearly equivalent.

Nutrient balances

Calculated nutrient balances indicated that organic apple orchards showed an unbalanced nutrient supply (Figs. 2 and 3). The diverging nutrient stoichiometries of the fertilisers and the nutrient offtakes are the main drivers of this result. None of the fertilisers used show a nutrient stoichiometry that corresponds with the nutrient offtakes from the fruits (Fig. 1). The low ratio of N to other nutrients in organic base fertilisers (Fig. 1) is due to N losses during storage, and might be increased by the process of composting where large N losses may occur (Li et al. 2010; Fukumoto et al. 2011; Yang et al. 2015; Möller 2018). Thus, their application can lead to surpluses of P, K and further elements when the application rates are designed according to the crop N demand. The opposite is true for many commercial organic fertilisers: the data indicated that an N fertilisation strategy based on these is often associated with negative balances of P, K, Ca and Mg. Consequently, achieving a balanced nutrition is not possible using only one single organic fertiliser. This challenge can be addressed by combining different fertiliser/input types (base fertilisers in combination with keratins, vinasse and/or biological N_2 fixation). In the present study most of the farmers used more than one fertiliser, leading to more balanced budgets in comparison with using only a single fertiliser. Why organic fruit famers use a specific fertiliser combination depends on different factors, mainly on different concepts for fertilization (use of "traditional" base fertilisers like compost and manure widely accepted in organic farming vs. contentious inputs like horn grit) but also on the regional availability of certain fertilisers. Both arguments are especially relevant in the case of bulky base fertilisers, which are only transported over short distances.

Manures and champost were thus not used in all regions, whereas compost is more commonly available or can be produced by the farmers themselves and was used in all regions. Many farmers prefer solid manures or composts as fertilisers as they pursue the goal of enhancing soil fertility and soil organic matter content. Keratin products and vinasse were used in all regions, because they have a high fertiliser effect and are easy to handle. Due to the high nutrient concentration combined with a low water content these products can easily be transported and stored. Other reasons may be the cost of fertilisers, their compatibility with available machinery for field application, or the intentional combination of different types of fertilisers to optimise plant nutrition.

We found that present budgets deviate from other studies: In South Tyrolean organic apple production systems, Alber et al. (2018) found substantial deficits in Ca and K, slightly negative P- and Mg-budgets and a slightly positive N-budget. However, they did not include inputs through pesticides while at the same time they did include outputs through removal of old trees at the end of the cultivation period of an apple orchard (assuming a production cycle of 20 years (Boschiero et al. 2015)). Therefore, the approach used by Alber et al. (2018) methodically led to lower nutrient inputs and higher outputs compared with the present approach. The present study focused on the budget in apple orchards at full yield, without considering inputs at the beginning (e.g., large amounts of organic amendments) nor outputs as tree biomass at the end of a growing cycle of trees. Yet, the removal of the trees at the end can be regarded as yearly nutrient output, since nutrient uptake into the tree biomass takes place every year. At the same time, nutrients in leaves and pruned branches do not affect the overall budget, since we assumed them to stay in the orchard and be recycled annually. At a yield of 17.1 Mg ha^{-1} year^{-1} with 18 kg N removal by the fruits, Link (2018) estimates a permanent storage in canopy and root of 15 kg N, 3 kg P, 12 kg K, 2 kg Mg and 37 kg Ca ha^{-1} year^{-1}. Another estimation indicates an uptake of 10–15 kg N ha^{-1} in the tree biomass in a mature orchard with an output of 15–20 kg N by the fruits in a yield of 30 Mg ha^{-1} (Dietz 1984). It is difficult to estimate whether these values can be transferred to organic farming, whether they are the same for every site and how the values change with different fertilisation rates. Moreover, our data deviated from these with a yield of 23.4 Mg ha^{-1} year^{-1} and 12 kg N removed by fruits. However, if these values are considered and the annual uptake and fixation in the tree biomass (which is removed from the field at the end of the production cycle) is included in the calculation, the outputs are higher. This consideration results in lower and, except for K, almost balanced nutrient budgets in the mean of the studied farms (10 kg N, 0 kg P, 0 kg Ca, 2 kg Mg and an increased imbalance of −16 kg K ha^{-1}). A fertilisation strategy incorporating all the approaches found in the orchards studied may thus achieve a more balanced nutrient input–output relationship. The mean values of an input of 36.6 kg N per ha and year with a 21.6% share of base fertilisers could be recommended as a guideline for balanced fertilisation, whereas the K deficit remains. Of course, these calculations depend on which fertilisers are included: Base fertilisers can show a variation in their nutrient concentrations and stoichiometries (Siedt et al. 2021), and of the commercial fertilisers, e.g. vinasse contains high amounts of K.

A general strategy to optimise fertilisation is to apply base fertilisers up to the quantity where the requirement of one nutrient is met (often P or K). The right amount can most accurately be achieved by analysing the nutrient content of the used material, or at least by using recent regional data of similar materials. The remaining N and other nutrient requirements could be added by other nutrient sources low in those elements for which the demand has already been fulfilled (e.g., keratin fertilisers). To balance nutrient input Möller (2018) suggests limiting the use of base fertilisers to 15–25% of the total N demand across the years. These numbers match our findings, where a ratio between 10 and 50% of total N applied by base fertilisers resulted in the most balanced nutrient budgets (Fig. 3), with a mean value of 21.6%. In contrast to the present findings, deficits in Ca and also in P and Mg (Alber et al. 2018), indicate a lower use of base fertilisers in South Tyrol, confirming that a complete omission of the use of base fertilisers may also result in imbalances.

Another approach to attain a balanced composition is the combination of fertilisers with N inputs via biological N_2 fixation, which are almost free from additional nutrient inputs. Small-seeded legumes like clover can fix N within the orchard, either in the tree-row below the trees or in the inter-row area. Growing them in the tree-row has the advantage that the plants grow where N is needed. This approach is only possible as green manure with a short growing period followed by incorporation into the soil. If legumes are established in the inter-row area, the fixed N can then be moved to the tree row by cutting and transferring the biomass. Establishing perennial legumes like white clover (*Trifolium repens*) was tested by our working group but proved to be difficult as clover establishment was not achieved to a sufficient degree and weed pressure was very high (Lepp et al. 2022a). Instead, using the inter-row biomass as fertiliser without any further alterations in species composition is already practiced by farmers (Lepp et al. 2022b). However, the biomass growth in the inter-row area is not in line with the N needs of the fruit trees. Plant growth in spring is slow and the first cut of the inter-row biomass cannot take place early in spring at the time of the highest N requirement of the orchard. Therefore, utilising inter-row biomass may pose challenges in synchronising N availability with crop N supply, necessitating a long-term approach to manage nutrient flows within the field that result from biomass transfer.

One major challenge persists in all these approaches, and that is the surplus of S. S outputs of apple orchards are very low, while S is introduced into the cropping system in several ways. The most important pathway is not related to fertilisation at all but is derived from the fungicides (Fig. 2) used to control *Venturia inaequalis*. In addition, efforts to compensate for a single nutrient deficit can lead to even higher S imbalances. For example, the compensation for the K deficit with K fertilisers approved in organic farming (such as potassium sulfate, K_2SO_4) would increase the S over-supply even further. Similarly, approaches to compensate for N deficits through fertilisation may increase S oversupply as well, as commercial organic fertilisers rich in N (like keratins and vinasse) are characterised by high S contents. With the high demand for fruit quality it is currently difficult to substantially reduce the S input via fungicides and reach a balance between input and output. However, since S is a necessary plant nutrient, toxicity does not seem to be an issue. Instead, liming should be considered to compensate for the acidifying effect on the soil.

Soil analysis

A correlation between nutrient budget and nutrient concentrations in the soil could not be detected (Fig. 5 and Table 2). In general, the current soil nutrient concentrations are related to least three driving factors: (I) the starting point at conversion to organic farming, (II) the supply of nutrients through external inputs in relation to the offtakes and (III) internal nutrient transfers from the inter-row area to the tree row.

Related to I), as data on the pre-conversion nutrient status of the soil was not available, it is difficult to detect relationships between fertilisation and the results of soil analysis. Other studies have found that the nutrient budget may not align with soil nutrient concentration (Alber et al. 2018; Reimer et al. 2020a). These studies have pointed out potential reasons for this, such as variations in the initial soil status of different farms at the time of conversion to organic farming, or the release of extractable nutrients from soil organic matter and the mineral phase of the soil. In the current study, a significant relation between K concentration in the soil and soil texture was found, however, without any relation to fertilisation (Table 2). The soil types in the different regions either were loess-based soils containing high amounts of K or very fertile Fluvisols. Even with a negative K budget, no K deficiency in the soil occurred (Table 1). Regional differences significantly influenced nutrient concentrations, C_{org} and pH (Table 2). These result from different site and soil conditions, linked to factors like climate that influence plant protection strategy, for example. Differences in soil pH between the regions cannot be explained by the orchards' current management strategies, as “Altes Land” and “Neckar” had the highest S input, while “Altes Land” and “Constance” had the lowest soil pH. The significant relationship between S concentration in the soil and the N ratio applied by base fertilisers (Table 2) could simply be caused by regional differences in the availability of base fertilisers and the higher need for plant protection in “Altes Land”, since both factors were highest in “Altes Land” and lowest in “Freiburg”. Furthermore, soil texture or pH influenced all the extractable nutrients in the soil, while at the same time pH was also affected by fertiliser application.

Regarding II), soil data in the present study supported the notion of nutrient imbalances in the assessed orchards, as soil extractable P, K and Mg concentrations in the tree row are very often higher than recommended. In 17% of the soils they are as much as two times higher than the recommended range. Even small annual positive budgets can lead to an accumulation of nutrients over the years. This effect is shown to a certain extent by the P content in the tree row, which increased in relation to the number of years of organic management (Table 2). The lower soil pH with the age of the apple trees and also with the number of years of organic management (Table 2) is in line with the assessment of the overall effect of fertilisation on soil reaction. It may be related to N- (mainly from commercial fertilisers) and S-inputs (from pesticides and organic fertilisers) resulting in an acidifying effect (Eq. 3), with S having the largest impact. In the soil, S reacts with water to sulphuric acid and thereby drives soil acidification ($2\ S + 2\ H_2O + 3\ O_2 \rightarrow 2\ H_2SO_4 \longleftrightarrow SO_4^{2-} + 2\ H^+$). This reaction mainly explains the acidifying effect of the pesticides (Fig. 2). Furthermore, decomposition of keratins is also related to a strong acidification process due to the oxidation of S and N—containing molecules. Similar to nitrate, sulphate surpluses in the soil can be leached during winter, dislocating other cations such as Ca and Mg due to equipotential bonding (Alva and Gascho 1991). Therefore, from the point of view of soil fertility, pesticides containing Ca (e.g., lime sulphur) should be preferred to those containing only S (elemental sulphur). In terms of liming effect, Ca had the strongest quantitative influence due to the influx of bases associated with cation inputs (mainly from base fertilisers: e.g., carbonate). The anions such as carbonate, associated with high inputs of cations like Ca, K and Mg through base fertilisers, alleviate the overall acidifying effect of fertilisation to a certain extent. The soil organic matter concentrations in the apple orchards studied seem to be at a typical soil level for orchards, as indicated by the data on regression analysis that did not show any relation of C_{org} content in the soil to fertilisation strategy or base fertiliser application. This observation is supported by the comparison of the soil organic matter content in the tree row and the inter-row area. While soil organic carbon is usually higher in grassland than in arable land (Jenkins 1988), in the present study the grassy inter-row area had slightly lower C_{org} contents than the tree row. This observation is probably due to regular inputs of organic matter through fertilisers and biomass from the inter-row area to the tree row, which simultaneously increase nutrient inputs into the tree row. In our analysis, years of organic management significantly influenced soil C_{org} content, but the coefficient of determination was low ($R^2 = 0.008$, Table 2).

The differences in P_{CAL} and K_{CAL} contents between the inter-row area and the tree row (Table 1, Fig. 4) can be explained by III), the regular transfer of biomass from the inter-row area to the tree row. The differences provide a hint that the very common use of inter-row biomass as mulching material for the tree row transfers considerable quantities of nutrients into the tree row (Jadczuk 1990; Engel et al. 2009; Surikova and Kārkliņš 2011). Mulch transfer is mainly applied in order to cover the soil surface for weed control and to reduce water evaporation in the tree row, as well as to enhance soil organic matter content (Lepp et al. 2022b). Engel et al. (2009) reported annual amounts of 10–25 kg N ha^{-1}, 15–25 kg K, 2–4 kg P, 3–5 kg Ca and 1–2 kg Mg, transferred from the inter-row area to the tree row via mulch material. These quantities are high enough to balance the K offtake and even increase the nutrient content in the tree row resulting in K accumulation over the years. This transfer does not affect the overall field budget, however it increases the imbalances of soil nutrient distribution within the orchard (Fig. 4) and may override the effects of balanced or imbalanced nutrient budgets. On the one hand, the inter-row area can be used as a nutrient source within the orchard to increase nutrient availability, especially through establishing legumes as N fixers (Granatstein et al. 2013). On the other hand, this promotes the depletion and accumulation of P and K (and other nutrients) in the inter-row area and the tree row, respectively. The soil data indicated that this practice has a stronger overall effect on soil K content than on P content (Fig. 4), probably due to the high K content in the above-ground biomass.

To reduce this imbalance between the tree row and inter-row area, farmers have several options: (a) to limit the amounts of nutrients transferred via a more targeted mulching, (b) by application of (base) fertilisers in the inter-row area instead of the tree row, and (c) in the long-term by alternating the position of the tree row and the inter-row area when old trees are substituted by new ones. Regarding a), considering that the highest N demand in the vegetative period is in spring and early summer (Paoletti et al. 2016), from the plant nutrition point of view the biomass cuts from the inter-row area should not be transferred to the tree row later in the year to avoid N oversupply during summer and to reduce nutrient depletion of the inter-row area. If the biomass is still transferred due to other reasons like ground cover for weed suppression or reduction of evaporation it could be considered to rake the material back to the inter-row after decomposition with suitable machinery. Regarding b), since base fertilisers have a very low N use efficiency in apple orchards, these fertilisers could be applied to the inter-row area to at least partially compensate for the nutrient transfer to the tree row, which again simultaneously supplies N to the apple trees. With regard to c), alternating the position of trees by planting the next tree generation into the inter-row area is suggested to avoid replant diseases anyway (Büchele 2018). However, this is not always feasible, e.g. due to hail net constructions or agri-voltaic systems installed above the tree row, but would also serve the purpose of shifting back the nutrients from the (former) tree row to the (former) inter-row area, regulating to some extent the transfer that has taken place within the field. However, the farmer has to take into account that the juvenile trees would be planted into low nutrient soil when they need most nutrients for their development, which needs to be mitigated by higher fertiliser applications in the first years of planting.

Conclusion

In organic apple production the overall nutrient demand is relatively low. Since nutrients are stored in the tree biomass, deficient nutrient supply can be buffered across years, resulting in fertilisation having a limited impact on overall yield. However, omitting fertilisation could result in soil depletion, first of K and N with the highest offtakes by apples, followed by P and other nutrients, with the risk of decreasing soil fertility in the long-term. Instead, the goal is to achieve recommended soil nutrient concentrations through long-term, balanced nutrient management. Soil analyses indicated that current management practices very often lead to a relative nutrient accumulation in the tree row beyond the recommended range, while the soil nutrients in the inter-row area are very often depleted.

While farmers focus on enhancing soil fertility by applying high amounts of base fertilisers, on sites with fertile soils we recommend to consider crop nutrient requirements and aim for a balanced nutrient input–output relationship to enhance nutrient efficiencies. A fertilisation strategy designed according to the crop N demand is often related to negative nutrient balances, if based on commercial fertilisers, or to nutrient surpluses where the fertilisation is based on base fertilisers like composts or solid animal manures. In combination, different input types with their respective nutrient stoichiometries can complement each other, namely an application of base fertilisers to amounts of about 20% of the total N demand across the years. Higher ratios of N applied via base fertilisers are neither beneficial for the yield nor for a balanced nutrient supply, as they lower the NUE as well as other nutrient efficiencies, due to oversupply. This implies that the current fertilisation strategies of organic fruit farmers in Germany that are often focused on the maintenance of soil fertility by application of base fertilizers and mulch from the inter-row need to be reconsidered.

As some commercial fertilisers are categorized as contentious due to their conventional provenance, the challenge remains to find suitable substitutions wherever keratin products from conventional origins are no longer permitted, for example in biodynamic farms (Demeter e.V. 2023). Since keratins are the only permitted fertilisers in organic farming that simultaneously have a high ratio of N to P and K, they can efficiently supply trees with N without further increasing soil P and K, which are often already high. Therefore, they are an important component for achieving balanced budgets in fruit orchards. Considering balanced nutrition and the concept of recycling nutrients, the critical approach to or even ban of keratin products should be reconsidered.

Cropping legumes in the inter-row area could be a substitution, bringing mainly N into the orchard system via biological N_2 fixation. However, the biomass needs to be shifted to the tree row, relocating P and K from the inter-row area to the tree row, and requires a long-term approach to manage the nutrient imbalances within the field. From a nutritional perspective, it is not recommended to transfer mulch from the inter-row area to the tree row when soil P and K levels within the row are already high. In this case, no base fertilisers, but only keratins should be applied. If the soil is high in P and moderate in K, transferring mulch can be suitable in limited amounts, as well as fertilisation with vinasse. If P and K in the tree row soil are both low, transferring mulch is beneficial. At the same time, farmers could consider placing compost into the inter-row area to avoid depletion there.

Furthermore, fertilisation strategies must be balanced with other components of orchard management like plant protection. Currently, it is challenging to significantly reduce S supply while maintaining fruit quality. To at least offset the acidifying effect on the soil, pesticides containing Ca should be preferred to those containing only S. Furthermore, additional liming should be considered if the liming effect of other fertilisers does not sufficiently reduce the acidifying effect of the overall system.

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Data availability The dataset generated and analysed during the current study is available from the corresponding author on request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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