



How does grain legume inclusion affect yield and N dynamics in a sugar beet crop rotation?

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Abstract Grain legume cultivation may offer benefits for subsequent crops regarding N supply and fertilizer reductions. However, legume effects on subsequently grown sugar beet (*Beta vulgaris* L.), before which cover crops may be cultivated, were hardly studied so far. In this study, pea (*Pisum sativum* L.) was compared to wheat (*Triticum aestivum* L.) as preceding crop before a succession of mustard (*Sinapis alba* L.) cover crop, sugar beet and winter wheat over four sequences in a long-term crop rotation trial near Göttingen, Central Germany. For all crops, yield, biomass, N uptake and soil mineral nitrogen before winter and in spring were analyzed. Pea compared to wheat as pre-crop was found to largely increase subsequent mustard cover crop biomass (+81%) and N uptake (+116%) as well as soil mineral nitrogen after mustard termination (+97%). This pre-crop effect was passed on to the following sugar beet which had higher taproot (+6%) and leaf biomass (+15%) as well as sugar yield (+4%) after pea, despite a partially lower N fertilization than after wheat. After sugar beet, soil mineral nitrogen and subsequent wheat yields were similar independent of the preceding main crops, despite a higher N amount in the sugar beet residues after pea. This may hint at a loss of N, necessitating careful adjustments of sugar

beet fertilization. Overall, we showed in our field trial that a preceding legume main crop offers benefits for subsequent sugar beet which could be used for a more sustainable sugar beet cultivation, using less fertilizer without losing yield.

Keywords Legume · Pre-crop · Nitrogen · Mustard cover crop · Wheat

Introduction

Grain legume inclusion in crop rotations may have benefits for the subsequently grown crops, as shown for cereals grown after legume pre-crops in a Europe-wide meta-analysis by Preissel et al. (2015), finding increased yields and reduced N fertilization demands in comparison to cereal pre-crops. More recently, Zhao et al. (2022) found similar benefits for a range of main crops following legumes compared to non-legumes in a global meta-analysis over hundreds of field experiments. Yet, the effect of legumes on subsequent sugar beet (*Beta vulgaris* L.) is much less known than for other crops of economic importance. Even in the otherwise exhaustive meta-analysis by Zhao et al. (2022), only one study with sugar beet is mentioned, with a large range of yield response to legume pre-crop (−7 to +111%) and without mentioning further details. In a recent study (Fenz et al. 2023) using satellite-derived NDVI values for thousands of combinations of pre-crop and subsequent crop across Austrian

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agricultural fields to determine pre-crop values from practice, only very few combinations feature sugar beet after faba bean or soybean, and not a single one sugar beet after field pea (*Pisum sativum* L.).

Previous results from the long-term crop rotation trial used for this study indicate a low and non-significant sugar yield benefit after pea compared to after winter wheat (*Triticum aestivum* L.; Koch et al. 2018). The positive effect on yield was larger when N fertilization was lower or omitted (Koch et al. 2018), fitting to results from the meta-analysis by Zhao et al. (2022) for other main crops and to results from Jacobs et al. (2018) from the same trial, finding that N fertilization for sugar beet may be reduced after pea. However, the N dynamics in this crop succession are not fully clear. In case of spring-sown crops such as sugar beet and preceding main crops harvested the previous summer, a cover crop may be grown in-between which would then act as a modifier of the potential pre-crop effect since the direct succeeding crop after the previous main crop would be the cover crop. This cover crop, in turn, would then be the directly preceding crop for sugar beet. Thus, potential benefits of a preceding legume main crop regarding N availability would first affect the cover crop, then this potentially modified cover crop could affect subsequently grown sugar beet.

At least for sugar beet, however, this transitional effect of cover crops was not yet analyzed for different preceding main crops within one trial to our knowledge, i.e. growing the same cover crop after different previous main crops. This may affect the chosen cover crop's properties greatly and may thus have a similar effect as the choice of the cover crop species itself after a given preceding main crop. In general, cover crop properties may have a large impact on subsequent sugar beet growth and N supply (Koch et al. 2022; Grunwald and Koch 2024). Adding to the potentially significant effect of cover crops on following sugar beet, surveys among sugar beet farmers in Germany found that the great majority of them use cover crops before sugar beet (Roß and Stockfisch 2022), thus there is a need to understand cover crops effects on sugar beet also from a practical perspective.

Increasing the N availability for and the N uptake of sugar beet by including a legume in the crop rotation as preceding main crop before sugar beet may also lead to an increase of the N content of above-ground sugar beet residues, which is already higher

than for many other crop residues. This may in turn lead to a higher N availability for the crop following sugar beet and thus have a benefit across the crop rotation. Alternatively, this additional N may be partially lost, since sugar beet leaves represent a potentially significant source of nitrous oxide emissions (Essich et al. 2020) and of nitrate leaching, also compared to other crop residues (Koga 2013). Either way, the N amount in sugar beet leaf residues is of importance in the assessment of agronomic measures in sugar beet cropping.

In this study, we analyzed the effect of field pea compared to wheat as pre-crop on a subsequent crop sequence of mustard (*Sinapis alba* L.) winter cover crop, sugar beet and winter wheat within a long-term crop rotation trial with regard to yield, overall biomass and N uptake of the studied crops as well as soil mineral nitrogen development over the crop sequence.

Material and methods

Study site and experimental design

The study site is a long-term arable field located near Harste in Lower Saxony, Germany (51°36'24.4"N 9°51'49.0"E). The soil at the site is classified as a Stagnic Luvisol with a silty loam texture (14% sand, 76% silt, 10% clay) and pH of 6.8 in the upper 30 cm. The concentration of relevant plant-available macro- and micronutrients in the topsoil was sufficient to enable high crop yields. Soil organic carbon content was 1.3% in the upper 20 cm at the beginning of the trial. Long-term (1991–2020) mean annual precipitation is 624 mm and mean annual temperature is 9.5 °C (DWD 2021).

The experiment started in 2006 comparing eight different crop rotations, with each crop rotation element cultivated every year (Koch et al. 2018). Plot size was 16.2 m × 14.0 m. A lattice design was used, resulting in three complete replications containing six incomplete blocks of four plots each. In each crop rotation, every crop rotation element was cultivated every year. Reduced tillage was carried out with a cultivator at a working depth of 18–20 cm. Mineral fertilization and plant protection were adapted to the crop, its rotational position and the year-specific growing conditions. Crop residues were generally left on the field.

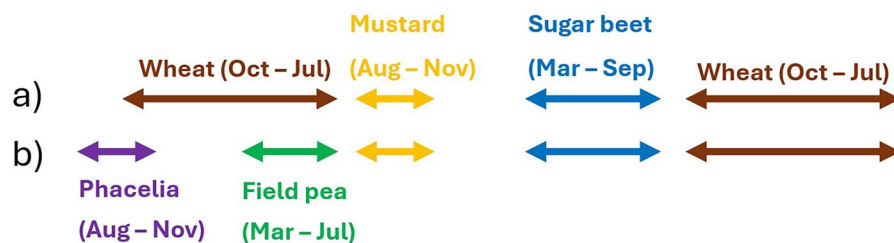


Fig. 1 Schematic depiction of the two cropping sequences compared in this study with either **a** Wheat as first-year crop followed by mustard, sugar beet and wheat or **b** Field pea as

first-year crop, preceded by phacelia cover crop and followed by mustard, sugar beet and wheat

Three different crop rotations were investigated:

- Winter wheat – mustard cover crop – sugar beet – winter wheat
- Winter wheat – mustard cover crop – sugar beet – winter wheat – Phacelia (*Phacelia tanacetifolia* L.) cover crop – silage maize (*Zea mays* L.)
- Phacelia cover crop – field pea – mustard cover crop – sugar beet – winter wheat – winter oil-seed rape (*Brassica napus* L.) – winter wheat – winter wheat

Between 2006 and 2018, crop rotation (ii) consisted of three years (main crops) only, being a wheat – silage maize – sugar beet rotation with mustard as cover crop before maize and no cover crop before sugar beet. Also, between 2006 and 2009, grain maize was grown instead of silage maize in that rotation.

Data of rotations (i) and (ii) were combined since they shared wheat grown in the first year. First-year crops wheat and field pea (the latter including preceding phacelia cover crop) were compared regarding effects on the succeeding crop sequence mustard cover crop, sugar beet and wheat following sugar beet. Figure 1 shows the cropping sequences analysed in this study. For this study, data from the study years 2018/2019–2023/2024 were included.

Agronomic management

Winter wheat was sown between October 1st and November 1st across the study years with the variety *Reform* used in 2018/19 and *Nordkap* in all subsequent years. Sowing density was between 375 and 450 grains m^{-2} and N fertilization ranged between 180 and 240 kg N ha^{-1} split in three to four applications

across the main growing season after winter. Harvest of wheat took place between July 30th and August 22nd. There was no general difference in agronomic management between the wheat preceding and the wheat succeeding sugar beet.

Cover crops, i.e. phacelia before pea in the first year and mustard before sugar beet in the second year, were sown between August 17th and 26th with a sowing density of 14 (phacelia) or 18 (mustard) kg ha^{-1} and a subsequent fertilization with 40 to 50 kg N ha^{-1} . Termination of phacelia and mustard was done by mulching between November 12th and 18th except for 2022 when it was done on December 14th.

Field pea (varieties used were *Astronaute* and *Alvesta*) was sown between March 14th and 29th and not fertilized with N. Harvest of field pea took place between July 18th and August 8th in the study years.

Sugar beet variety changed from year to year (*Lisanna* in 2020, *Colledia* in 2021, *Lunella* in 2022 and *Annarosa* in 2023). Sowing date was between March 24th and 31st from 2020 to 2022 and on April 21st in 2023. Sowing took place in rows of 45 cm distance with an intra-row seed distance of 18.3 cm. In the harvested subplots, seeding density was initially higher and later manually singled out. Machine harvest of sugar beet was between September 26th and 29th in the four study years.

N fertilization of sugar beet was varied between the crop rotations in 2020 (130 kg N ha^{-1} after wheat and 70 kg N ha^{-1} after pea) and 2021 (110 kg N ha^{-1} after wheat and 80 kg N ha^{-1} after pea), while in 2022 and 2023 all treatments received the same amount (125 kg N ha^{-1} in 2022 and 110 kg N ha^{-1} in 2023). Fertilization calculation considered the soil mineral N levels in spring, the fertilization recommendation for sugar

beet as well as practical aspects. In the mean over the four study years, sugar beet after pea received 96 kg N ha⁻¹ and sugar beet after wheat 119 kg N ha⁻¹.

Total N supply of sugar beet, i.e. soil mineral nitrogen (SMN) in spring plus N fertilizer, was the same after both preceding main crops in the mean over the four years (154 kg N ha⁻¹), although N supply in the single study years was partially higher after wheat (in 2020 and 2021; by 24 and 7 kg N ha⁻¹, respectively) or after pea (in 2022 and 2023; by 16 and 17 kg N ha⁻¹, respectively) since N fertilization did not consequently follow spring SMN values for practical reasons.

Crop management including pesticide use followed the recommendations of the regional extension service of the federal state of Lower Saxony partially adapted according to the personal experience of the technicians responsible for the trial. Weeds, pests and leaf spot diseases were effectively controlled by pesticides.

Plant and soil analyses

Sampling took place for four three-year sequences each starting one year after the previous (Tab. 1), resulting in four study years for each crop rotation element, with the first year (wheat or phacelia + pea) being analysed from 2018/19 to 2021/22, the second year (mustard + sugar beet) from 2019/20 to 2022/23 and the third year (wheat) from 2020/21 to 2023/24. Due to the design of the experiment, each three-year sequence was grown on different plots, except for rotation (i) for which the plots for the first and fourth sequence were the same due to the length of the rotation being only three years.

Cover crop biomass was determined directly before cover crop termination by sampling either four subplots with 0.25 m² each or two subplots with 0.5 m² each, depending on the year, resulting in a total sampling space of 1 m². No biomass was determined

for phacelia in 2018, thus only the period 2019–2021 is considered for phacelia.

Concerning wheat and pea, a sample of above-ground biomass from roughly 1 m² per plot was taken shortly before harvest and separated into grain and straw biomass for determination of the grain to straw ratio. Dry matter grain yield was determined by combine-harvesting a subplot of 21 m² and straw biomass dry matter was calculated from the grain to straw ratio.

Sugar beet leaf biomass (including the crown as the uppermost cm of the taproot) was manually determined shortly before harvest on 6.3 or 12.6 m², depending on the year, while taproot biomass was harvested on 12.6 m². After harvest, taproots were washed to determine taproot fresh weight and processed to brei on which a polarimetric sugar content analysis according to ICUMSA (1994) was done. Sugar yield was determined by multiplying fresh taproot yield by sugar content.

All dried (105 °C) biomass samples (cover crop biomass, wheat grain, wheat and pea straw, sugar beet leaves and taproot brei) were afterwards analyzed for C and N contents by dry combustion (FlashEA 1112, Thermo Fisher Scientific, Waltham, MA, USA) using two lab replicates.

Soil samples were taken each year in the beginning of December and either in February (in case of wheat plots, during wheat growth) or March (in case of sugar beet plots, before sugar beet sowing) in 0–30, 30–60 and 60–90 cm soil depth to determine SMN. Samples were taken as composites of five subsamples per plot. For analysis, 20–50 g of fresh soil was extracted with 0.0125 M CaCl₂ solution (ratio 1:4) (VDLUFA 2020). Results are given as sum of nitrate and ammonium in kg N ha⁻¹.

Statistical analysis

Statistical analyses were performed with R version 4.1.1 (R Foundation for Statistical Computing, Vienna, Austria). Differences between the first-year

Table 1 Study years for the single crop rotation elements across four three-year sequences

	1st sequence	2nd sequence	3rd sequence	4th sequence
1st year: Wheat or phacelia + pea	2018/19	2019/20	2020/21	2021/22
2nd year: Mustard + sugar beet	2019/20	2020/21	2021/22	2022/23
3rd year: Wheat	2020/21	2021/22	2022/23	2023/24

main crops regarding biomass, C and N content and C:N ratio of subsequent mustard, sugar beet leaves and taproots, and wheat grain and straw as well as total N uptake of sugar beet and wheat and SMN levels over the cropping sequence were analyzed by a linear mixed model with preceding or pre-preceding main crop as fixed effect and year, replication and plot as random effects. Residuals of the models were checked for homoscedasticity by Levene's test as well as graphically and for normal distribution by the Shapiro–Wilk test as well as graphically.

Results

Mean field pea grain yield was $3.6 (\pm 1.3)$ Mg ha⁻¹ across the four study years with mean annual values varying between 1.7 Mg ha⁻¹ and 5.1 Mg ha⁻¹. Mean wheat grain yield of the first-year wheat was $8.3 (\pm 0.9)$ Mg ha⁻¹, varying between 7.6 and 9.0 Mg ha⁻¹. Residue biomass was similar for pea and wheat when including phacelia as cover crop before pea in the calculation to cover a similar timeframe in the field (Tab. 2). Pea and phacelia combined left around 7 Mg dry matter biomass ha⁻¹ on the field (with phacelia biomass ranging between 2.2 and 5.2 t ha⁻¹ and pea residue biomass ranging between 2.4 and 4.1 Mg ha⁻¹), compared to 7.7 Mg ha⁻¹ by wheat, ranging between 7.1 and 8.8 Mg ha⁻¹. However, biomass-N left on the field by phacelia and pea was around three times the amount left by wheat straw, with the C:N ratios of both phacelia biomass and pea straw clearly lower than that of wheat straw (Tab. 2).

Subsequent mustard, grown as cover crop before sugar beet, benefited from pea as preceding crop with a nearly twice as high biomass after pea (5.8 t ha⁻¹) compared to after wheat (3.2 Mg ha⁻¹) and similar

Table 3 Mustard dry matter biomass, N and C content in biomass and biomass C:N ratio after two preceding crops for the study years 2019 to 2022. Data are means with standard deviations in brackets (n=12 for field pea pre-crop and n=24 for wheat pre-crop). Different letters show significant differences between the preceding crops ($p < 0.05$)

Pre-crop	Dry matter [Mg ha ⁻¹]	N content [kg N ha ⁻¹]	C content [Mg C ha ⁻¹]	C/N ratio [-]
Wheat	3.2 (1.6) ^a	77 (40) ^a	1.3 (0.7) ^a	16.8 (3.8) ^b
Field pea	5.8 (2.6) ^b	166 (65) ^b	2.3 (1.2) ^b	13.6 (3.1) ^a

differences for biomass-C (2.3 Mg C ha⁻¹ compared to 1.3 Mg C ha⁻¹) and -N (166 kg N ha⁻¹ compared to 77 kg N ha⁻¹), while the C:N ratio of mustard biomass after pea was lower than after wheat. The differences were significant in all cases (Tab. 3). Variation of mustard biomass across the study years was very high, yet mustard biomass after pea was clearly higher than after wheat in all years (data not shown).

Sugar beet leaf biomass, taproot fresh yield and sugar yield were all significantly higher after preceding main crop pea than after wheat, with increases of 15% for leaf biomass, 6% for taproot biomass and 4% for sugar yield (Tab. 4). Differences in sugar yield were mainly due to differences in taproot yield, as sugar concentrations varied only between 17.0% (after pea) and 17.3% (after wheat) in the mean. Also, amino-N content in the taproot varied only slightly between $5.2 (\pm 1.1)$ and $5.7 (\pm 1.2)$ mmol kg⁻¹ after wheat and pea, respectively.

Grain yield of wheat following sugar beet was very similar for the pre-preceding main crops field pea and winter wheat with $8.8 (\pm 0.5)$ and $8.7 (\pm 0.5)$ Mg dry matter ha⁻¹, respectively. Straw biomass was also not significantly different with $8.5 (\pm 1.5)$ and $7.8 (\pm 1.0)$ Mg dry matter ha⁻¹ after pre-preceding pea and wheat, respectively.

Table 2 Crop residue (straw) dry matter biomass, N and C content in biomass and biomass C:N ratio of the first-year crops wheat and field pea (including phacelia cover crop before pea) for the study years 2018/19 to 2021/22 (in case of phacelia only 2019/20 to 2021/22). Data are means with standard

Crop	Straw [Mg ha ⁻¹]	Straw-N [kg N ha ⁻¹]	Straw-C [Mg C ha ⁻¹]	Straw C/N ratio [-]
Wheat	7.7 (1.2)	41 (13)	3.4 (0.6)	88 (17)
Phacelia	3.5 (1.4)	94 (28)	1.3 (0.6)	13 (4)
Field pea	3.6 (1.3)	28 (8)	1.4 (0.3)	51 (10)

deviations in brackets (n=24 for wheat, n=12 for pea, n=9 for phacelia). No statistical analysis was conducted due to the structural differences between the preceding crops concerning the number of crops grown within one cropping year

Table 4 Sugar beet leaf biomass (dry matter), fresh taproot yield and sugar yield after two preceding main crops for the study years 2020 to 2023. Data are means with standarddeviations in brackets (n=12 for preceding main crop pea and n=24 for wheat). Different letters show significant differences between the preceding main crops ($p < 0.05$)

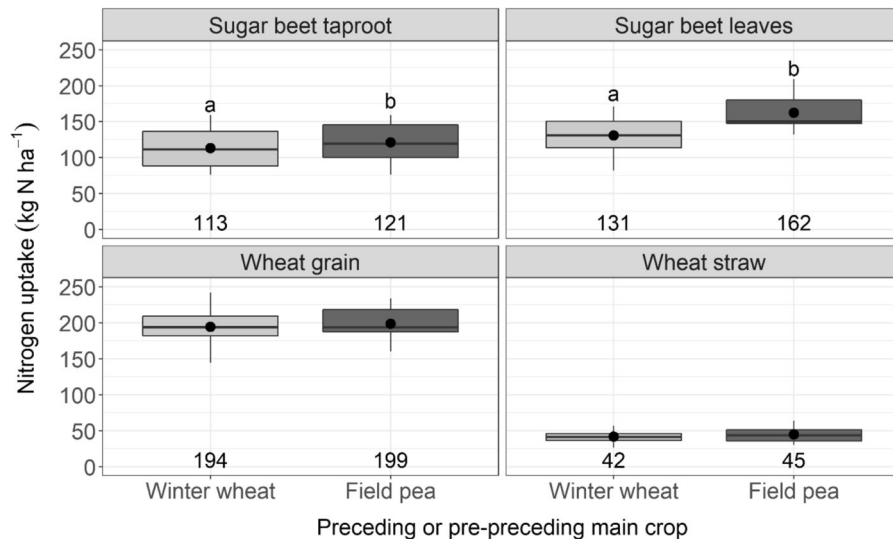
Preceding main crop	Leaf biomass dry matter [Mg ha ⁻¹]	Taproot fresh yield [Mg ha ⁻¹]	Sugar yield [Mg ha ⁻¹]
Wheat	6.1 (0.8) ^a	91.6 (6.8) ^a	15.8 (1.5) ^a
Field pea	7.0 (0.7) ^b	97.4 (7.2) ^b	16.5 (1.5) ^b

Nitrogen uptake of sugar beet was significantly increased after pea compared to after wheat, more so for the leaves than for the taproot (Fig. 2). For both leaf and taproot biomass, the higher uptake after pea was due to a higher biomass since N concentration did not differ strongly (data not shown). N uptake in the grain and straw biomass of wheat grown after sugar beet was very similar for both pre-preceding crops (Fig. 2).

Soil mineral N contents in 0–90 cm soil depth around mustard termination in December were significantly higher after preceding crop pea than after wheat with twice as high values (73 compared to 37 kg N ha⁻¹). Before sugar beet sowing in March,

SMN was still significantly higher after pea than after wheat (Fig. 3). The decrease of SMN over winter from the 0–90 cm soil depth was higher after pea than after wheat, with single-year differences between December and March ranging between +1 and -42 kg N ha⁻¹ after pea and between +8 and -12 kg N ha⁻¹ after wheat.

Under wheat following sugar beet, SMN in December was slightly, yet not significantly lower after pre-preceding main crop wheat compared to pea, while values in February, shortly before fertilization in wheat, were equal between the two variants (Fig. 3). Notably, SMN was lowest in December 2023 with around 50 kg N ha⁻¹ in both treatments after months with high precipitation, compared to values between 80 and 130 kg N ha⁻¹ in the other study years (data not shown).

**Fig. 2** Taproot and leaf N uptake of sugar beet following either field pea or winter wheat as preceding main crop (for the study years 2020 to 2023) as well as grain and straw N uptake of wheat as second subsequent crop (for the study years 2021 to 2024). The bar in the box shows the median while the large

dot shows the mean (n=12 after pea and n=24 after wheat) which is also shown as number below the box. Different letters show significant differences between the preceding or pre-preceding main crops ($p < 0.05$)

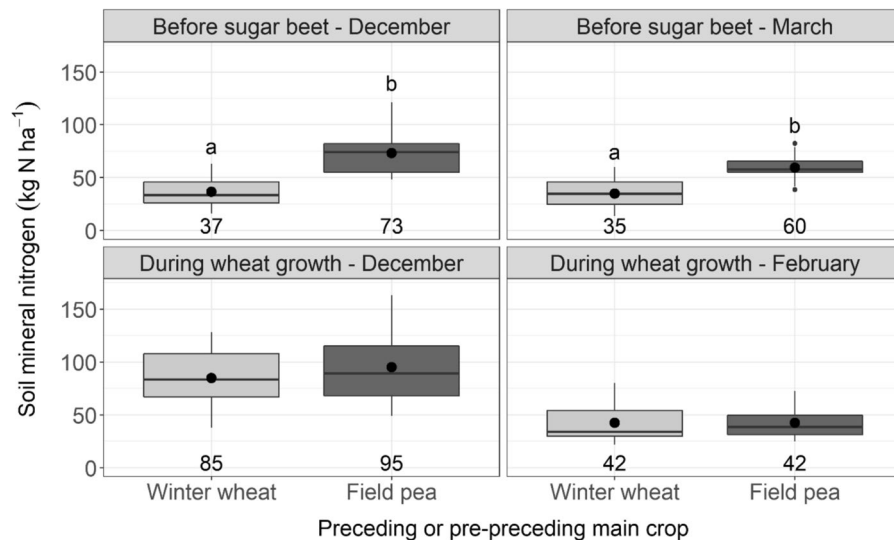


Fig. 3 Soil mineral nitrogen (nitrate and ammonium) contents in 0–90 cm soil depth after preceding main crops field pea and winter wheat before the first subsequent crop sugar beet in December (around mustard termination) and in March (before sugar beet sowing) for the study years 2019/20 to 2022/23 as well as during the early growth of the second subsequent main crop winter wheat in December and February for

the study years 2020/21 to 2023/24. The bar in the box shows the median while the large dot shows the mean ($n=12$ for first-year crop pea and $n=24$ for first-year crop wheat) which is also shown as number below the box. Different letters show significant differences between the preceding or pre-preceding crops ($p < 0.05$)

Discussion

Phacelia cover crop and subsequent pea main crop both left a residual biomass with a lower C:N ratio than wheat, increasing the potential N supply for the subsequent crop. While pea yields varied more strongly over the years than wheat yields, as can be expected when comparing a legume to a winter cereal (Reckling et al. 2018), the straw biomass of pea varied to a lesser extent and the N amount in the biomass even less; thus, the straw-N amount was rather stable. However, belowground residues, i.e. roots and rhizodeposition, which were not sampled in this study, are of a much larger relevance for the N supply of the subsequent crop (Arcand et al. 2014; Taveira et al. 2020). Regarding rhizodeposition, Wang et al. (2020) found that legumes on average deposit 83 kg N ha⁻¹, a quarter of which was found to be taken up in subsequently grown wheat. Thus, also the belowground residues of pea might represent a large source of N for the subsequent crop.

Concerning mustard cover crop after pea or wheat, the overall mean values for dry matter biomass in our study (3.2 after wheat and 5.8 Mg ha⁻¹ after pea)

were similar to the range (3 – 5.5 Mg ha⁻¹) of mustard biomass found by Björkman et al. (2015) for several site/years in the USA and also to the mean value (4.5 Mg ha⁻¹) found by Elhakeem et al. (2021) for several site/years in Germany and the Netherlands; thus, mustard growth in our trial in general appears to represent usual conditions. Despite the equal N fertilization for all mustard plots (which was given to ensure an evenly and fully established cover crop in all crop rotations for consistency reasons despite potentially not being necessary after pea), mustard after pea accumulated nearly twice as much biomass as mustard after wheat and seems to have strongly profited from the presumed higher N availability as similarly found for main crops following legumes, particularly under low N fertilization (e.g. in the meta-analyses by Preissel et al. 2015 and Zhao et al. 2022). Total aboveground biomass N in mustard biomass after pea (166 kg N ha⁻¹) also greatly surpassed the values found for mustard after wheat (77 kg N ha⁻¹) and also the similar mean value for mustard across different sites of 79 kg N ha⁻¹ found by Elhakeem et al. (2021). This is due to the lack of a dilution effect by the higher biomass on the N concentration,

which might have been expected in case of a much higher biomass in a given crop. In fact, N concentration in the mustard biomass was even slightly higher after pea than after wheat (data not shown), indicating the overall much higher N uptake as probable reasons for the increased growth.

Accordingly, the higher mustard biomass accumulation after pea also did not lead to a higher C:N ratio but instead even a significantly lower ratio (13.6) for mustard after pea compared to mustard after wheat (16.8) and also compared to the mean value of 24.4 for mustard presented by Elhakeem et al. (2021). This may increase the chance that the N included in the mustard biomass will be available for the subsequent crop and might thus reduce the potential need for increased fertilization after cover crops (Koch et al. 2024). Also, as mentioned above, the N fertilization of mustard after pea, while maintained in the trial for consistency and continuity, could potentially be left out, decreasing the overall N fertilizer amount needed for the sequence of cover and main crop after pea. Indeed, in sugar beet cultivation in Germany, currently more N is applied with than without using cover crops, mainly due to cover crop fertilization (Roß and Stockfisch 2022). This could potentially be avoided after pea pre-crop.

After pea and the following mustard cover crop, significantly more SMN was present in the soil than after wheat and mustard. Although part of the additional N was lost from the upper 90 cm of soil over winter, i.e. between December and March, potentially leading to an increased N leaching and thus loss of available N from the soil, SMN levels in March were still significantly higher after pea than after wheat. In this value, biomass N of pea (or wheat) and mustard residues that has already been mineralized will be included to a certain share; yet, a less readily available share of biomass residues will probably be mineralized at a later stage, potentially increasing the difference between wheat and pea pre-crop due to the larger amount of N stored in mustard after the latter. In a previous study on the same trial, Koch et al. (2018) also found higher SMN levels after pea in March (study years 2011 to 2013) and, in unfertilized subplots under subsequent sugar beet, indeed an even higher difference by May. Thus, N supply for sugar beet grown after pea and a cover crop in-between can be assumed to be higher than after wheat, similarly to winter-sown main crops grown after legumes.

The cover crop between the two main crops does not appear to modify this significantly.

The higher SMN level in spring after preceding main crop pea allows for a reduction of N fertilization, however, in the study period this was only done in two of four years. In the other two years, all sugar beet plots received the same amount of N fertilization. This decision was only partially due to rather similar SMN levels between the different crop rotations in those years, but more for practical reasons. Still, SMN differences between preceding main crops pea and wheat in 2022 and 2023, when fertilization was equal, was lower ($< 20 \text{ kg N ha}^{-1}$) than in 2020 or 2021 ($20 \text{ to } 50 \text{ kg N ha}^{-1}$; data not shown), when sugar beet fertilization was reduced after pea. In a previous study on the trial, Jacobs et al. (2018) mentioned a reduction of N fertilization of 45 kg N ha^{-1} after pea compared to wheat for the study years 2011–2014. This and the range reported here (reduction of 30 or 60 kg N ha^{-1} in 2020 and 2021) fit well to data reported for cereals in the meta-analysis of Preissel et al. (2015), finding possible reductions of N fertilization of up to 30 kg N ha^{-1} for maximum yields and up to 60 kg N ha^{-1} for acceptable yields after legume compared to cereal pre-crops. With that in mind, it can reasonably be assumed that taproot and sugar yields after pea would also have been at least similar to, if not higher than, taproot and sugar yields after wheat in 2022 and 2023 if N fertilization in those years had also been reduced by around 30 kg N ha^{-1} as would have been reasonably possible to do, particularly given the lower dependence of sugar beet on N fertilization in comparison with cereals.

Taproot and sugar yields were higher after pea than after wheat on average as well as in every single study year, albeit with varying effect sizes (data not shown). The generally positive effect of pea on subsequent sugar beet compared to wheat as preceding main crop was also found in the earlier study on the trial by Koch et al. (2018). In that study for the study years 2011–2013, however, different N fertilization levels were tested additionally, and pea only had a significant effect on sugar yield at zero or low N fertilization, while for optimal or surplus fertilization, the effect was smaller. Similarly, in the present study, with all plots fertilized at least optimally, the difference between sugar beet after pea and after wheat was, while significant, rather small with a 4% increase in sugar yield. In this regard, sugar beet

seems to be similar to other crops, since a larger effect of preceding legume main crops on subsequent main crops' yield at lower compared to higher N fertilization is also reported in the meta-analyses by Preissel et al. (2015) and Zhao et al. (2022), focusing only or mostly on cereals. Still, aside from the long-term trial reported here, hardly any results on the reaction of sugar beet to preceding legume main crops are available, with the exhaustive global meta-analysis from Zhao et al. (2022) only mentioning one study with a large range of yield reaction from slight losses to a doubling of yields. Thus, the similar yield effect of preceding legume main crops on sugar beet compared to cereals needs to be confirmed for other sites and growing conditions.

Reasons for the improved sugar beet growth after pea might include a higher N supply also beyond the level found at the spring SMN sampling due to mineralization of pea and mustard biomass after this date. However, all plots were fertilized at an optimum N level and sugar beet, in contrast to other crops, may not be expected to react strongly to additional N (Märlander et al. 2018). Also, a higher yield was found after pea for all single study years in this study (data not shown), even when sugar beet after pea received the same amount of N fertilizer as after wheat despite higher SMN levels. It can thus be assumed that the N supply of sugar beet after wheat was optimal, so the increased N supply after pea might not have mitigated any kind of N limitation to sugar beet growth.

In case of a lacking N limitation, soil structural improvements, which may facilitate taproot growth underground (Koch 2009), were previously noted as potentially decisive in determining sugar beet yield (Grunwald and Koch 2024). Koch et al. (2018) also found that the sugar yield benefit after pea results from a larger taproot biomass, not a higher sugar content, which is also the case for the present study. As soil structure may further be more beneficial after high- than after low-biomass cover crops (Grunwald et al. 2023), a possible benefit of pea beyond N might thus be that the increased biomass of mustard grown after pea improved the soil structure and, ultimately, growing conditions for the following sugar beet compared to the lower mustard biomass growth after wheat. However, since this was not analysed in this study, further research is needed to confirm this potential effect.

Beyond taproot and sugar yield, the higher N availability after pea also resulted in a significantly increased N uptake in the sugar beet leaf biomass. Since the leaf N amount is a potentially significant source of N₂O emissions (Koga 2013; Essich et al. 2020) and a high leaf biomass in the second half of the growing season is not required for high yields (Hoffmann and Kenter 2018), this could rather be seen as a negative effect of the increased N supply after pea, particularly as a harvest of the leaves for other purposes, such as using them as animal feed, is currently not feasible (Jacobs et al. 2024). However, N₂O measurements at different levels of sugar beet leaf N content would need to confirm the extent of the issue of gaseous N emissions, since greenhouse gas emission measurements after sugar beet are rare. Still, adjusting the N fertilization of sugar beet to the expected N supply seems strongly advisable after pea or another preceding legume to save fertilizer (and greenhouse gas emissions associated with fertilizer production) and to avoid increased N₂O emissions in the field following sugar beet harvest. However, sugar beet leaf N content was also increased in those study years in which N fertilization for sugar beet after pea was lower than after wheat (2020 and 2021; data not shown), hinting at generally increased leaf N amounts after pea which may not be completely adjusted by simply lowering the N fertilization according to SMN conditions found in spring.

Surplus N being lost to the environment via gaseous emissions and leaching might represent an especially relevant issue when growing grain legumes before sugar beet due to the already N-rich leaf residue material of sugar beet being further enriched in N. According to the German fertilizer ordinance (DüV 2017), 10 kg N ha⁻¹ should be subtracted from the planned fertilizer amount if grain legumes were grown as preceding main crop. In case of sugar beet, a higher subtraction seems advisable, given the lower dependence of sugar beet on N supply compared to crops such as cereals, maize and rapeseed, and the higher risks connected to excessive N in the sugar beet residues. However, in a previous study on the trial, Jacobs et al. (2019) noted that, on the other hand, greenhouse gas emissions for sugar beet cultivation after pea may be reduced by the lowered amount of N fertilizer necessary to achieve similar yields compared to after wheat, saving the emissions connecting to fertilizer production. Thus, the total

emissions summed up over various pathways might also be lower when incorporating pea before sugar beet. This needs to be confirmed by other studies in various growing environments, since the cited studies of Jacobs et al. (2018, 2019), Koch et al. (2018) and the present study were all conducted in the same long-term experiment.

While potential N losses caused by increased N amounts in the leaf biomass need to be considered, a subsequently grown crop in the field might also profit from mineralization of the leaves and thus a higher N supply which could represent a continuation of the N benefit from pea to the main crop grown in the second year afterwards. However, no positive effect of the increased leaf N amount on subsequently grown winter wheat could be found in this study. Differences between pea and wheat as pre-preceding main crops regarding SMN contents in December and February under the third-year wheat were small and not significant. For the single years, differences were small as well (data not shown) and accordingly, there was no differentiation in wheat fertilization among the crop rotations. This underlines the need for agronomic measures to keep the sugar beet leaf N content as low as possible as the surplus N might be lost to the environment if it is not immobilized in soil organisms, since it does not appear in the measured pools (SMN or subsequent crop biomass) anymore. However, neither gaseous and leaching losses nor immobilization were analysed in this study, so the fate of the additional N in the sugar beet leaves is unclear. In any case, this additional N in the system apparently does not benefit the subsequent crops in the crop rotation.

Grain and straw yield and as well as N uptake of wheat following sugar beet were all numerically, yet not significantly higher after pre-preceding main crop pea than wheat, indicating that any possible benefits of pea in the crop rotation, which might extend to more than just additional N, are not present anymore for the second subsequent main crop. This lack of a pre-preceding main crop effect of pea on wheat two years later was similarly found by Sieling and Christen (2015) and Rose et al. (2023), for pea and faba bean, respectively, however, in both cases, the directly preceding crop before wheat was winter oilseed rape which itself is an advantageous pre-crop for wheat, more so than sugar beet (Groeneveld et al. 2024) and thus, the oilseed rape benefits were apparently merely not further increased by a pre-preceding grain

legume. Yet, in the present study, there was also no modifying effect in case of sugar beet as pre-crop for wheat, possibly because the additional N stored in the crop residues of sugar beet is quickly mineralized due to the leaves' low C:N ratio (< 20) and subsequently lost or immobilized before it can be used by the following wheat which only takes up low amounts of N during early growth. Thus, sugar beet does not appear to pass the benefits of a preceding grain legume on to the next (main) crop.

Concerning the N balance regarding N in- and outputs, N fertilization in the whole crop sequence (mustard – sugar beet – wheat) following either wheat or pea as first-year crops was reduced by 23 kg N ha^{-1} after pea in the mean of the four years, while the N removal by the harvested material (sugar beet taproot or wheat grain) was slightly increased ($+8$ and $+5 \text{ kg N ha}^{-1}$, respectively) and the N in the crop residues remaining in the field (mustard biomass, sugar beet leaves and wheat straw) was partially strongly increased ($+84$, $+34$ and $+4 \text{ kg N ha}^{-1}$). The fate of the latter is unclear and should be the subject of future studies. Overall, a stronger reduction in fertilization of sugar beet and a general reduction of the cover crop fertilization after pea could result in an even more favorable balance for pea as preceding crop and a lower risk of pollution.

Conclusion

Pea as preceding main crop was found to increase subsequent mustard cover crop and sugar beet growth. The plant growth and potential N fertilizer saving benefits for sugar beet were similar in extent to previously published results for preceding grain legume benefits on cereals, leading to a positive evaluation of the inclusion of pea before sugar beet in terms of fertilizer reductions without associated yield losses. However, preceding pea also led to increased N uptake into the sugar beet leaf biomass, representing a potential source of N emissions. In winter wheat following sugar beet, no large effect of pre-preceding pea could be found anymore, neither concerning plant growth nor necessary fertilization, thus there appears to be no general benefit from pea for the second subsequent main crop after sugar beet and, specifically, no benefit of the increased N amount in sugar beet residues. Thus, the reduction of N fertilization to

sugar beet is not only advisable in economic terms but also necessary in order to not produce excess N for the plant. The fate of the additional N particularly in the sugar beet leaves needs further examination. Overall, the findings of this study need to be confirmed for other environmental and agronomical conditions since there are hardly any studies on effects of preceding legume main crops on subsequent sugar beet cultivation.

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Author contributions Both authors contributed to the study conception. Material preparation, data collection and analysis as well as the writing of the first draft were done by D.G.. H.-J.K. initiated, designed and supervised the long-term field experiment used in this study and commented on previous versions of the manuscript. Both authors read and approved the final manuscript.

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Data availability The datasets used in this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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