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RESEARCH ARTICLE

Cover crop effects on fibrous roots and growth of subsequent sugar beet

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Abstract
Purpose Cover crops (CC) may increase root growth of the following main crop by improving the soil structure, however, the extent of this effect might depend on the CC species. This study aims at quantifying the effects of different CCs on sugar beet (SB; *Beta vulgaris* L.) fibrous roots and plant growth.
Methods Two field trials were conducted near Göttingen, Central Germany, with SB after four CC treatments: fallow, oil radish, saia oat, and spring vetch, differing in biomass. SB root length density and biomass was analyzed to 60 cm soil depth in July, around 100 days after sowing. From June on, plants were sampled monthly to determine leaf and taproot biomass. CC biomass and SB residues were further analyzed for carbon content.
Results SB root length density in 0–20 cm soil depth was increased by the CCs, particularly radish and oat, while in lower depths only non-significant differences were found. Differences between the CC treatments regarding SB leaf and taproot biomass were site-specific with increases in SB biomass after CCs at a site with high N supply, yet no effects on sugar yield were found for either site. Carbon input into the soil was significantly increased through CC cultivation by 47 to 85%.
Conclusion CCs with different properties improved fibrous root and overall plant growth of SB to a different extent at sites with contrasting conditions. Future studies under diverse environmental conditions are needed to fully assess the potential benefits of CCs on following SB growth.

Keywords Root length density · Fibrous root biomass · Cover cropping · Saia oat · Spring vetch · Oil radish

Introduction

Cover crops may improve the soil structure compared to winter fallow by rooting activity and the input of additional organic material (Blanco-Canqui et al. 2015). Among the possible benefits, increases in soil aggregation and alleviations of soil compaction by cover crop roots are rapid improvements which may already occur after the first year of cover cropping (Blanco-Canqui et al. 2015; Williams and Weil 2004). Large differences in cover crop root biomass (Wendling et al. 2016; Grunwald et al. 2023), however, might lead to a different extent of these benefits, with stronger effects associated with cover crops with a high root biomass (Grunwald et al. 2023). Moreover, cover crop root channels (Williams and Weil

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2004) or newly created macropores by cover crop growth (Colombi et al. 2017) might be directly used by the subsequent main crop. The choice if and which cover crops to grow is thus of potentially high importance for the subsequent crop.

Sugar beet (*Beta vulgaris* L.) needs a quick canopy development to achieve high yields (Malnou et al. 2006) and may thus profit from an improved soil structure and facilitated root growth. Brown and Biscoe (1985) even suggested that sugar beet roots in deeper soil layers only colonize existing root channels and macropores left by pre-crops. Additionally, as newly formed sugar beet roots may need some time to be able to take up water and nutrients after reaching a certain soil depth (Fitters et al. 2017), a faster root development may mitigate stress in case of drought. Even small advantages concerning sugar beet root length density might lead to large effects on water use and consequently nutrient uptake, as sugar beet roots were found to be more efficient regarding water uptake than e.g. wheat roots (Brown and Biscoe 1985; Windt and Märländer 1994; Fitters et al. 2017). Stevanato et al. (2011) furthermore related an increased sugar beet root length density to a lower weed density due to a higher competitiveness of sugar beet. However, in previous studies, a higher sugar beet root length density was not generally connected to higher sugar yields (Fitters et al. 2022; Windt and Märländer 1994) which was explained with a possible trade-off between increased water and nutrient uptake capacities and the costs of root proliferation (Fitters et al. 2022). A facilitated root growth through an improved soil structure might reduce these costs for the plant, resulting in more assimilates left for yield increase.

Beyond advantages of an improved root length density for plant growth and yield, increases in sugar beet root biomass could directly benefit soil carbon levels in fields grown with sugar beet. In the soil, root biomass is stabilized for a longer period than aboveground crop residues (Kätterer et al. 2011; Poeplau et al. 2021). Because of the comparatively low fibrous root biomass of sugar beet (Bolinder et al. 2015; Pacholski et al. 2015), sugar beet cultivation could be considered unfavorable to attempts to sequester carbon in agricultural soils or even to maintain current levels of soil carbon. Thus, increasing sugar beet root biomass could positively impact the evaluation of sugar beet cultivation in terms of climate change mitigation. However, studies reporting sugar beet root biomass and especially its variation depending on agronomic measures are scarce, demanding a closer look at possible effects of cover crop cultivation on sugar beet roots. Additionally, the cover crop biomass itself, if not harvested, serves as carbon input into the soil with large variations among different cover crops (Grunwald et al. 2023).

In a previous study on the field experiments used here, Grunwald et al. (2023) found benefits of cover crops regarding soil structure, indicated by an increased aggregate stability and a reduced penetration resistance, compared to fallow under subsequent sugar beet. Possibly connected to this, early sugar beet growth until May was partially improved compared to fallow. The aims of this study were to investigate whether the positive effect of cover crops on early sugar beet growth can also be found for later growth stages, and if this was associated with an enhanced root network of sugar beet. We hypothesized (i) a higher sugar beet root length density and root biomass after cover crops than after fallow, (ii) an improved sugar beet growth after cover crops, and (iii) stronger effects for cover crops with a high (root) biomass than for cover crops with low (root) biomass.

Materials and methods

Trial sites and experimental design

Two field experiments with sugar beet grown after four different cover crop treatments were conducted in a typical sugar beet growing area in Central Germany. The two trial sites were located in Hevensen (2018/19; 51°38′13.2″N 9°53′35.5″E) and Niedernjesa (2019/20; 51°28′22.9”N 9°54′53.1″E) near Göttingen, Germany. The soil at both sites is classified as a Luvisol (IUSS Working Group WRB 2015) with clay contents of 119 and 143 g kg^{-1}, silt contents of 849 and 709 g kg^{-1} and sand contents of 32 and 148 g kg^{-1}, respectively, while soil organic carbon content in the topsoil was 12.0 and 13.8 g C kg soil^{-1} and total N content in the topsoil was 1.24 and 1.46 g N kg soil^{-1}, respectively. The long-term annual precipitation in the region is 624 mm and the mean air temperature 9.5 °C (DWD 2021). Weather conditions for the trial years are shown in Table 1. Precipitation differed largely between the years and was below average in Hevensen and clearly above average in Niedernjesa.

Table 1 Monthly mean temperature and precipitation sum as well as mean or sum over the growing period for the two field experiments, with deviations from the long-term means (1991–2020) in brackets

	Hevensen 2019		Niedernjesa 2020	
	Mean temperature [°C]	Precipitation sum [mm]	Mean temperature [°C]	Precipitation sum [mm]
April	10.1 (+1.0)	33 (−2)	10.5 (+1.4)	64 (+28)
May	11.4 (−1.5)	81 (+18)	12.3 (−0.6)	51 (−13)
June	20.2 (+4.3)	51 (−15)	17.9 (+2.0)	119 (+54)
July	19.0 (+1.1)	49 (−23)	18.1 (+0.2)	37 (−35)
August	19.7 (+1.8)	56 (−8)	20.3 (+2.4)	132 (+69)
September	14.2 (+0.3)	35 (−14)	14.9 (+1.0)	30 (−19)
Total	15.8 (+1.2)	305 (−43)	15.7 (+1.1)	432 (+84)

At both sites, combine-harvested field pea (*Pisum sativum* L.) was grown as pre-crop and harvested at the end of July (30 July 2018 for Hevensen, 31 July 2019 for Niedernjesa). Pea straw was left in the field and ploughed under shortly before cover crop sowing. The experiments were designed as two-factorial randomized split-plot trials with four replicates organized in blocks. Four cover crop treatments served as main plots (21.0 × 17.0 m), consisting of (i) bare fallow control, (ii) saia oat (*Avena strigosa* Schreb.), (iii) oil radish (*Raphanus sativus* var. *oleiformis* Pers.) and (iv) spring vetch (*Vicia sativa* L.). As subplots (2.7 m × 14.0 m = 37.8 m^2), subsequent sugar beet received different amounts of N fertilization, from which only the one aiming at an optimal N supply is considered here, resulting in the application of 60 kg N ha^{-1} in Hevensen and 100 kg N ha^{-1} in Niedernjesa. Sugar beet after oil radish in Niedernjesa deviated from this scheme and received a fertilization of 200 kg N ha^{-1} for experimental reasons not connected to the analyses in this study. The total number of plots was 4 replicates × 4 treatments = 16 and the total experimental area 16 × 37.8 m^2 = 604.8 m^2.

Cover crops were sown in rows with a width of 12.5 cm on 29 August 2018 in Hevensen and on 8 August 2019 in Niedernjesa. Sowing density was 30 kg ha^{-1} for oil radish, 80 kg ha^{-1} for oat and 90 kg ha^{-1} for vetch. The cover crops developed well except for oat in Niedernjesa which was probably due to a virus infection. Other than that, vetch had a lower biomass than radish at both sites (see also Table 3). At Hevensen, oat, radish and vetch were killed by frost in January 2019. At Niedernjesa, frost at the end of November 2019 severely damaged vetch, while oat died because of senescence and radish survived without frost damage. Before sugar beet sowing, all plots were treated with glyphosate (5 l ha^{-1}). Soil tillage took place by rigid tine cultivator tillage to 15 cm depth in all plots.

Seedbed preparation for subsequent sugar beet cultivation was performed with a light tine harrow. Sugar beet seeds were sown on 9 April 2019 in Hevensen and on 3 April 2020 in Niedernjesa. Row spacing was 45 cm and seed density within the row was 7 cm. N fertilizer was manually applied as calcium ammonium nitrate shortly after sowing. In the 4–6 leaf stage, plant populations were thinned to the final stand of 100,000 plants ha^{-1}.

Plant aboveground biomass and root sampling and analyses

Aboveground biomass of cover crops was determined in November at the end of the vegetation period on 4 × 0.5 m^2 per main plot. Biomass of sugar beet leaves and taproots was determined at both sites at four dates (17 June 2019, 12 July 2019, 14 August 2019, and 2 September 2019 for Hevensen, and 17 June 2020, 14 July 2020, 12 August 2020, and 8 September 2020 for Niedernjesa) on 5.4 m^2 per plot. For the June sampling date, only whole plant biomass was sampled and counted as leaf biomass due to the small amount of taproot biomass. Additionally, leaf and taproot biomass as well as sugar yield were determined at harvest which took place on 25 September 2019 in Hevensen and 1 October 2020 in Niedernjesa.

Roots of the cover crops were sampled in November at the end of the vegetation period, while roots of subsequent sugar beet were sampled in July (16 July 2019 in Hevensen, 98 days after sowing (DAS) and 14/16 July 2020 in Niedernjesa, 102/104 DAS).

Eight (cover crops at both sites, sugar beet in Hevensen) or ten (sugar beet in Niedernjesa) soil core samples (70 mm diameter for the cover crops at both sites and sugar beet in Hevensen, and 60 mm diameter for sugar beet in Niedernjesa) were taken per plot to a depth of 50 (sugar beet in Hevensen) or 60 cm (cover crops at both sites, sugar beet in Niedernjesa). Due to dry soil conditions in July in Hevensen, a deeper sampling was not possible. For the sugar beet root samplings, half of the samples in each plot were taken between the sugar beet rows and the other half within the rows, while the cover crop root sampling points were spread randomly across the plots. The samples were divided in the depths of 0–20, 20–40 and 40–50 or 40–60 cm.

Fibrous roots were washed out of the samples by water, were then manually cleaned from plant residues, spread on a glass plate with a tweezer and scanned (Epson Perfection V700 Photo, Epson, Suwa, Japan). The resulting images were analyzed for total root length and mean root diameter with the software WinRHIZO 2019 (Regent Instruments, Quebec, Canada), from which root length density (RLD) was calculated by referring to the sample volume. For sugar beet at the Hevensen site, values for 40–50 cm were considered representative for the 40–60 cm soil depth. Afterwards, the fibrous root samples were dried and weighed, from which the root biomass per hectare was calculated by considering the sampling area. In the case of oil radish, the taproot biomass was added to the total belowground biomass. For sugar beet at Hevensen, values from the 40–50 cm soil depth were doubled to reach comparable values to Niedernjesa. For the cover crops, the data of the eight samples per plot were averaged. For sugar beet, the data for the four (Hevensen) or five (Niedernjesa) samples per plot and sampling position were averaged.

Dry matter content of leaves, taproots and fine roots was determined by drying at 60 °C for 48 h. Sugar beet leaf and taproot biomass as well as cover crop above- and belowground biomass was further analyzed for C content by dry combustion (FlashEA 1112, Thermo Fisher Scientific, Waltham, MA). Sugar beet root samples were not analyzed for C content. As approximation, a C content of 45% was assumed which is used frequently as assumption of plant C contents and which is close to what was found by Redin et al. (2014) for root biomass of numerous crops. Sugar yield was determined by multiplying the fresh matter of the taproots with the sugar content of the taproot brei which was analyzed polarimetrically (ICUMSA 1994).

Statistical analyses

The statistical data evaluation was carried out with R version 4.1.1. The differences between the cover crop treatments regarding subsequent sugar beet roots in different sampling positions for the single trial sites were analyzed by linear mixed models with cover crop treatment and sampling position (within or between the rows) as well as their interaction as fixed effects, and block and cover crop nested in block as random effects. In all cases, the interaction between cover crop treatment and sampling position was not significant and removed from the model. The differences between the cover crop treatments regarding subsequent sugar beet aboveground growth for leaf and taproot biomass as well as cover crop and sugar beet residue carbon input for the single trial sites were analyzed by linear mixed models with cover crop treatment as fixed effect and block as random effect.

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. If the factor cover crop was significant ($p < 0.05$), estimated marginal means (package 'emmeans') were compared by a Tukey test (via command 'cld').

Results

In Hevensen, sugar beet root length density in 0–20 cm soil depth was significantly increased by oat and radish as pre-crops compared to fallow, with values after vetch in-between and close to fallow (Fig. 1). In Niedernjesa, values after radish, grown with increased sugar beet N fertilization, were clearly and significantly higher than after the other treatments. In both years, differences in 20–60 cm soil depth were not significant. Sampling position did not affect the cover crop effect on root length density, however, in both years, root length density in 0–20 and 20–40 cm soil depth was significantly higher between than within the rows, while in 40–60 cm soil depth it was vice-versa in Hevensen

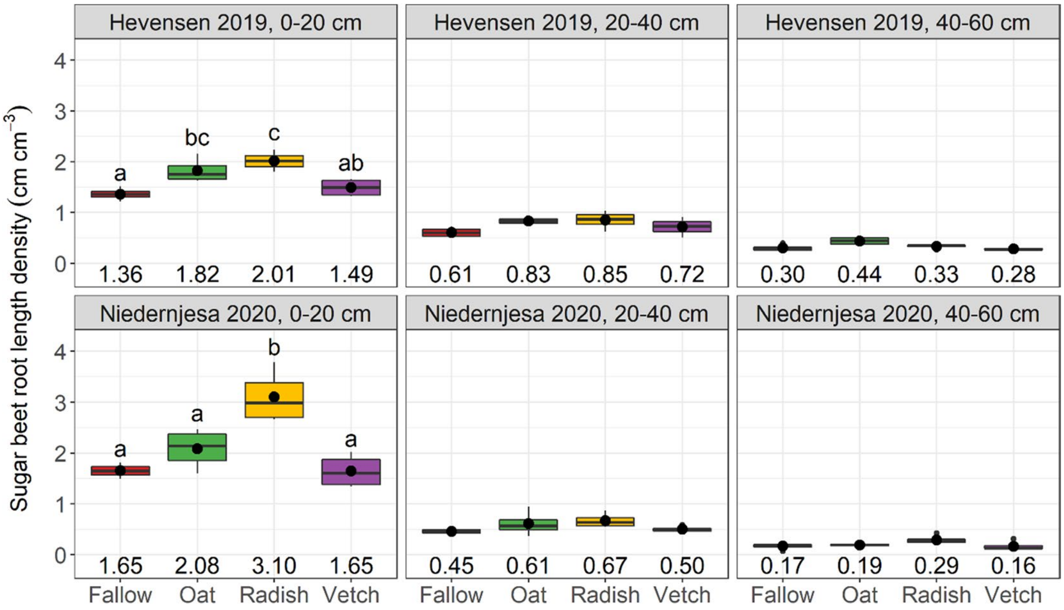

Fig. 1 Sugar beet root length density in July after four cover crop treatments at two sites in three soil depths, averaged over samples taken within and between the rows. Horizontal bars in the boxes show the median, while large dots and numbers at the bottom show the mean ($n = 4$). Different letters indicate significant differences between the cover crops treatments. Note that sugar beet after radish in Niedernjesa 2020 received the doubled amount of N fertilizer compared to the other treatments

and not significantly different in Niedernjesa (data not shown).

Average sugar beet fine root diameter did not vary significantly between the cover crop treatments at any depth at both sites (data not shown). In Hevensen, mean values for the cover crop treatments ranged between 0.140 and 0.146 mm in 0–20 cm, between 0.164 and 0.172 mm in 20–40 cm and between 0.169 and 0.187 mm in 40–60 cm soil depth. In Niedernjesa, mean values ranged between 0.139 and 0.150 mm in 0–20 cm, between 0.143 and 0.150 mm in 20–40 cm and between 0.159 and 0.180 mm in 40–60 cm soil depth.

Total sugar beet fine root biomass in 0–60 cm showed a similar pattern to the root length density, with highest values after radish and oat and lowest after fallow (Fig. 2), however, differences were only significant between radish on the one side and fallow and vetch on the other in Niedernjesa. Average sugar beet root length density in 0–60 cm soil depth correlated significantly ($p < 0.001$) with total fine root biomass with R = 0.71 in Hevensen and with R = 0.93 in Niedernjesa.

Sugar beet aboveground biomass development after the cover crop treatments was different at both sites (Table 2). In Hevensen, a significant positive effect of the cover crops on whole plant biomass compared to fallow was partially visible in June and, regarding leaf biomass, also in July. In August, no effect on leaf biomass was found, while values in September were lower after oat and radish compared to fallow. Similar to the final sugar yield, taproot biomass did not differ among the cover crop treatments at any sampling date including harvest, although values were highest for fallow at harvest (Fig. 3).

In Niedernjesa, only radish with additional N fertilization showed higher sugar beet biomass values than the other treatments in June (significant only in comparison to fallow and oat). From July onwards, both leaf and taproot biomass tended to be higher after all cover crops compared to fallow, however, this was only partially significant. At harvest, there was no significant difference between the treatments regarding taproot and sugar yield, although fallow had the lowest values.

Total C input by cover crop and subsequent sugar beet cultivation was significantly higher for the treatments with cover crops than for fallow in both years with increases of between 47 and 85% (Table 3). This was mainly due to the cover crop biomass itself and partially, in particular in 2020, due to increased input

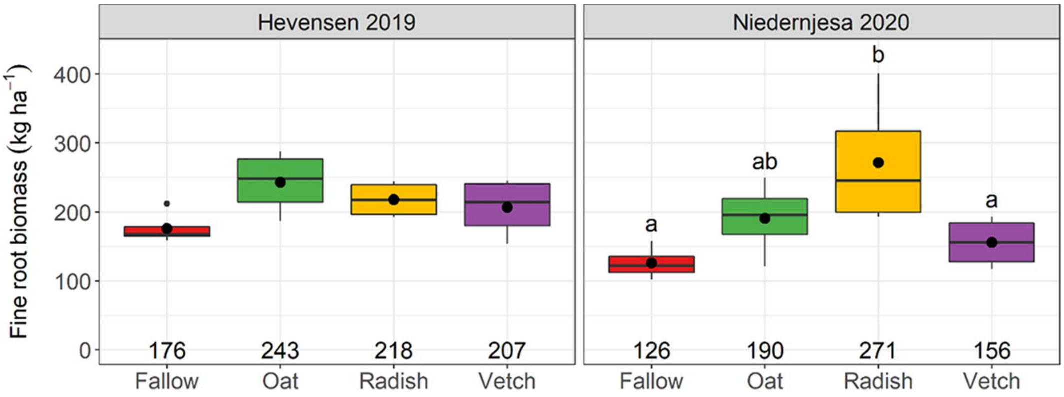

Fig. 2 Sugar beet fine root biomass in July in 0–60 cm soil depth after four cover crop treatments at two sites. Horizontal bars in the boxes show the median, while large dots and numbers at the bottom show the mean ($n = 4$). Different letters indicate significant differences between the cover crops treatments. Note that sugar beet after radish in Niedernjesa 2020 received the doubled amount of N fertilizer compared to the other treatments

of sugar beet leaf residues, while sugar beet belowground residues were of a lower importance.

Discussion

Overall sugar beet root growth

The values found for sugar beet root length density in the upper 60 cm of soil in this study are similar to values found in several other studies for July or around 100 DAS (Brown and Biscoe 1985; Fitters et al. 2022; Garz et al. 1992; Koch 2009; Pacholski et al. 2015; Windt and Märländer 1994). Thus, sugar beet root growth in our study can be assumed to represent typical growth patterns. However, gains and losses in root length density in all soil depths might occur between July and sugar beet harvest depending on water availability (Brown and Biscoe 1985; Fitters et al. 2022; Garz et al. 1992; Windt and Märländer 1994). Nonetheless, as drought stress in June or July is more detrimental to sugar beet growth and subsequently final yield than drought later in the season (Brown et al. 1987; Ebmeyer and Hoffmann 2022), adequate root development until July appears to be of a high importance to avoid potential yield losses.

In contrast to the rather typical values for root length density, the range of 126 to 271 kg ha^{-1} for sugar beet fibrous root biomass from 0 to 60 cm soil depth found in this study is rather low compared to previous results, with e.g., van Noordwijk et al. (1994) reporting around 350 kg ha^{-1} in the upper 60 cm, depending on treatment. However, these results were found for a sampling in the beginning of September when, compared to our sampling date in mid-July, additional root growth might have taken place. Similarly, Pacholski et al. (2015) found 284 kg sugar beet root biomass ha^{-1} at the end of June while at maximum root expansion 480 kg ha^{-1} were found. Thus, the absolute values found for sugar beet root biomass in our study may not represent the total belowground crop residue input of sugar beet at the time of the final harvest in autumn.

Root biomass in 0–60 cm soil depth was closely correlated to root length density as there was only a small variation in root diameter across cover crop treatments and soil depths. Overall, root diameter was low, ranging between 0.14 and 0.19 mm, compared to, e.g., 0.3 mm down to 60 cm soil depth found by Fitters et al. (2022) and between 0.2 and 0.3 mm in 0–60 cm soil depth found by Koch (2009) for similar sampling dates. This might indicate a generally low penetration resistance and/or the absence of significant barriers to root growth in the soils of this study, as sugar beet root diameter was found to positively correlate with penetration resistance and bulk density (Koch 2009), leading to a lower root biomass at a similar root length density compared to previous studies. However, sugar beet root diameter is also variable over the growing period, with lower root diameters found at later stages of plant development in the same depth (Fitters et al. 2017, 2022).

Table 2 Sugar beet leaf and taproot biomass [Mg dry matter ha^{-1}] following four cover crop treatments at two sites and five sampling dates. Data shown are means with standard deviations in brackets ($n = 4$)

		Hevensen 2019		Niedernjesa 2020	
		Leaf	Taproot	Leaf	Taproot
June[1]	Fallow	2.5 (0.2)^{a}		2.9 (0.4)^{a}	
	Oat	2.8 (0.1)^{ab}		2.9 (0.3)^{a}	
	Radish	3.0 (0.3)^{b}		3.7 (0.4)^{b}	
	Vetch	2.8 (0.3)^{b}		3.1 (0.3)^{ab}	
July	Fallow	4.6 (0.7)^{a}	6.7 (0.7)	5.3 (0.5)^{a}	5.6 (0.6)^{a}
	Oat	5.3 (0.4)^{b}	7.2 (0.4)	5.3 (0.4)^{a}	5.9 (0.6)^{ab}
	Radish	5.2 (0.5)^{ab}	6.5 (0.4)	6.5 (0.3)^{b}	6.5 (0.2)^{ab}
	Vetch	5.4 (0.4)^{b}	6.8 (0.4)	6.0 (0.5)^{ab}	6.8 (0.5)^{b}
August	Fallow	6.0 (0.4)	13.9 (0.5)	7.1 (0.2)^{a}	12.2 (0.4)^{a}
	Oat	6.0 (0.5)	14.4 (0.7)	8.3 (0.8)^{ab}	14.6 (1.5)^{b}
	Radish	5.3 (0.8)	14.1 (0.7)	9.3 (0.4)^{b}	15.1 (0.9)^{b}
	Vetch	6.1 (0.2)	14.6 (0.8)	8.2 (0.5)^{ab}	13.6 (1.4)^{ab}
September	Fallow	7.4 (0.7)^{b}	19.4 (0.2)	7.1 (0.7)^{a}	19.1 (1.6)^{a}
	Oat	6.1 (0.4)^{a}	20.2 (0.9)	8.4 (0.9)^{ab}	22.5 (1.3)^{b}
	Radish	6.2 (0.2)^{a}	20.3 (0.4)	8.6 (0.8)^{ab}	21.9 (1.0)^{ab}
	Vetch	6.8 (0.3)^{ab}	20.4 (0.4)	9.2 (0.8)^{b}	20.9 (1.4)^{ab}
Harvest	Fallow	6.7 (0.8)	21.9 (1.3)	6.7 (0.2)^{ab}	23.1 (0.6)
	Oat	6.4 (0.6)	21.1 (0,7)	6.6 (0.3)^{a}	24.2 (1.4)
	Radish	5.8 (0.6)	20.6 (0.7)	6.8 (0.4)^{ab}	24.1 (0.8)
	Vetch	7.1 (0.7)	20.6 (1.3)	7.6 (0.6)^{b}	24.0 (0.8)

Different letters indicate significant differences between the cover crops treatments for one date. Note that sugar beet after radish in Niedernjesa 2020 received the doubled amount of N fertilizer compared to the other treatments

[1] Biomass sampling in June considered only the whole plant which was mostly leaf material

Overall, besides this apparent lack of physical barriers to extended sugar beet root growth, the relatively low root length density between 40 and 60 cm, also in comparison to other studies (Brown and Biscoe 1985; Fitters et al. 2022; Garz et al. 1992; Koch 2009), might indicate generally non-limiting conditions for sugar beet growth in terms of water and nutrient supply at the study sites, as otherwise root proliferation might have been greater below 40 cm. This was even more pronounced at Niedernjesa compared to Hevensen. The reason for this might be an excessive N supply through mineralization at the Niedernjesa site, as was mentioned by Koch et al. (2022) who found a clearly higher N uptake of unfertilized sugar beet at this site compared to Hevensen, independent of cover crop treatment. Also, while at neither site drought conditions were prevalent, precipitation in Niedernjesa was nearly 50% higher than in Hevensen and also higher than the long-term average. Thus, the overall conditions in Niedernjesa appear to have been optimal for sugar beet growth and probably did not necessitate a strong, above-average root growth.

Cover crop effects on sugar beet root growth

The effects of the cover crops on sugar beet root growth in 0–20 cm soil depth were similar at both sites with a positive effect of radish compared to fallow and no effect of vetch, while a positive effect of oat compared to fallow was only found in Hevensen, despite numerically higher values also found in Niedernjesa. The effects of the cover crops on total sugar beet root biomass in 0–60 cm soil depth were similar to those for root length density, with higher values particularly after oat and radish compared to fallow, although the only significant difference was found between radish and fallow in 2020. Below 20 cm, no significant effects were found at either site.

The higher root length density and partially higher root biomass of sugar beet after radish and oat compared to fallow and vetch might be connected to improvements in soil structure, as a higher soil aggregate stability and lower penetration resistance, both facilitating root growth (Koch 2009), were found in the trials studied here after cover crops with high biomass compared to fallow (Grunwald et al. 2023). Also, sugar beet roots might reuse existing root channels and biopores left by the cover crops (Colombi et al. 2017; Williams and Weil 2004). The lower and non-significant differences between cover crop treatments below 20 cm might be connected to a lower cover crop root biomass with depth and to the missing incorporation of aboveground residues in that soil depth, and thus an overall lower effect of the cover crop treatment.

However, another reason for the increased sugar beet root growth after radish and oat might be a higher need for the plant to invest in a higher root length because of limitations concerning N supply. For the trial in Hevensen, Koch et al. (2022) have shown for unfertilized sugar beet subplots that N mineralization after cover crops tended to be lower than after fallow in the second half of the vegetation period, leading also to a negative effect on sugar beet N uptake. This may be caused by a delayed mineralization of the N

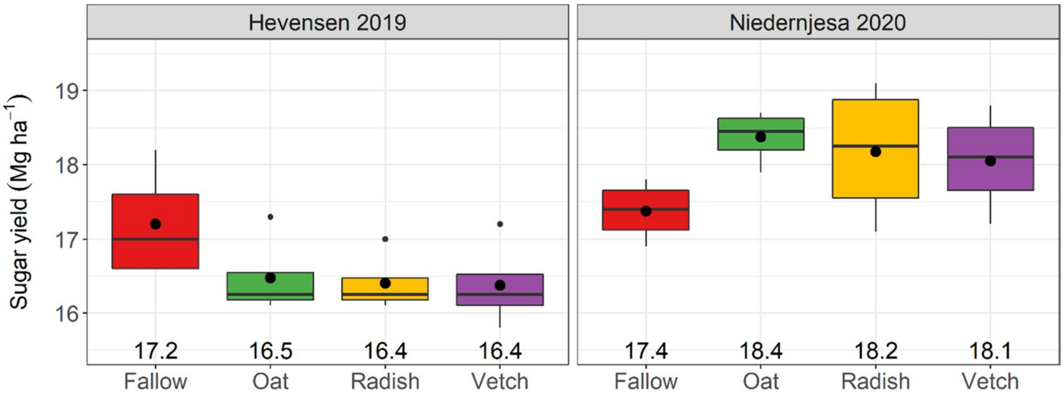

Fig. 3 Sugar beet yield after four cover crop treatments at two sites. Horizontal bars in the boxes show the median, while large dots and numbers at the bottom show the mean ($n = 4$). Different letters indicate significant differences between the cover crops treatments. Note that sugar beet after radish in Niedernjesa 2020 received the doubled amount of N fertilizer compared to the other treatments

Table 3 Biomass C input [kg C ha^{-1}] by above- and belowground residues of cover crops (data from the end of the vegetation period) and subsequent sugar beet (aboveground data from September, belowground data from July) at two sites

		Aboveground residues		Belowground residues (0–60 cm)		Total input
		Cover crop	Sugar beet	Cover crop	Sugar beet	
Hevensen 2019	Fallow		2268 (206)^{ab}		79 (11)	2349 (203)^{a}
	Oat	1140 (37)^{c}	2108 (236)^{a}	268 (22)^{b}	109 (21)	3757 (70)^{b}
	Radish	979 (6)^{b}	2322 (119)^{ab}	207 (29)^{b}	98 (12)	3696 (128)^{b}
	Vetch	667 (26)^{a}	2578 (152)^{b}	120 (21)^{a}	93 (19)	3450 (159)^{b}
Niedernjesa 2020	Fallow		2835 (307)		57 (11)^{a}	2892 (307)^{a}
	Oat	687 (85)^{a}	3303 (455)	195 (36)^{b}	86 (24)^{ab}	4271 (431)^{b}
	Radish	1181 (86)^{c}	3486 (451)	545 (72)^{c}	122 (44)^{b}	5349 (400)^{c}
	Vetch	880 (116)^{b}	3579 (422)	108 (22)^{a}	70 (17)^{a}	4643 (400)^{bc}

Data shown are means with standard deviations in brackets ($n = 4$). Different letters indicate significant differences between the cover crops treatments

taken up during cover crop growth and represents a certain disadvantage of cover cropping regarding the N supply of following sugar beet. Thus, the plant may be forced to a more intensive rooting by the increased need after cover crops to access N in the soil. Possibly, both processes, a beneficial effect of cover crop growth on soil structure and root growth conditions and a disadvantageous effect of cover crop N uptake on N supply of the subsequent crop, are taking place in parallel and result in the values found in this study.

In Niedernjesa, N supply was generally much higher than in Hevensen, thus an N limitation of sugar beet growth by the cover crops seems unlikely (Koch et al. 2022). Due to this, it could also be assumed that the higher fertilization of sugar beet after radish did not alter the results in a significant manner, as N supply, especially at the root sampling date in July, was probably more than sufficient to meet the demands of the plants anyhow. In addition, sugar beet root growth can be expected to generally be lower when N supply is higher (Brown and Biscoe 1985; Pacholski et al. 2015). As root growth was in turn particularly high after oil radish and the higher N fertilization, it seems unlikely that the higher N availability in this treatment caused these values. We would rather assume that the results in Niedernjesa, including radish, might represent only the beneficial effects of cover crop growth on subsequent sugar beet, i.e. soil structural improvements, without the possible negative effects on N supply. As cover crop effects on sugar beet root growth in Niedernjesa were only visible in the topsoil it could thus be assumed that below 20 cm there were no positive effects of the cover crops on soil structure. However, as root growth below that layer and particularly below 40 cm was generally weak, probably due to a lack of necessity for the plants, the effect of cover crop treatment on sugar beet root growth below 20 cm might simply not have become apparent at this site.

Differences between the cover crops in the extent of their effect on sugar beet root growth are probably connected to the different biomass accumulated by the crops. Oat and radish can generally be expected to accumulate a higher above- and belowground biomass and, correspondingly, a higher N uptake than vetch, which in our case led to both, a stronger positive effect on soil structure (Grunwald et al. 2023) as well as a stronger negative effect on N supply, also due to a higher C:N ratio of radish and oat compared to vetch biomass (Koch et al. 2022). Belowground biomass of oat and radish was clearly higher than that of vetch in both years (see also Table 3), yet vetch had a higher aboveground biomass than oat in Niedernjesa which was presumably due to a virus infection of oat in that year. This inhibited growth of oat might have contributed to the lower and non-significant difference of sugar beet root length density after oat compared to fallow and vetch in that year.

Oil radish had the highest above- and, particularly, belowground biomass in Niedernjesa and while this fits to the strongest positive effect on subsequent sugar beet roots, particularly in the topsoil where the largest part of radish root biomass including the taproot was concentrated (Grunwald et al. 2023), the increased sugar beet fertilization (200 kg N ha^{-1}) in comparison to the other treatments (100 kg N ha^{-1}) has to be noted here again. However, as N supply at this site was excessive anyhow (Koch et al. 2022), as discussed above, this result might indeed represent a positive effect created by the large input of organic material by oil radish in case of a lacking negative effect on N supply. This would also explain the clearly larger effect of oil radish in Niedernjesa compared to Hevensen, where radish biomass accumulation was considerably lower and thus weaker effects on soil structural properties could be expected.

Overall, the relative increase in sugar beet root length density and root biomass by cover crops over the whole soil profile might be greater in situations with a certain limitation to sugar beet growth, such as drought conditions or sites with reduced N fertilization or availability. If N availability is lower, sugar beet root growth was found to increase in order to acquire possible nutrients (Brown and Biscoe 1985; Pacholski et al. 2015). This can be seen in our data when comparing the sampling depths 20–40 and 40–60 cm from both sites with higher values for Hevensen with a lower N supply. Concerning water availability, Camposeo and Rubino (2003) note that a high soil water content in the upper soil increases sugar beet root length density in the topsoil and decreases roots in deeper layers. This might be the cause behind the overall larger root length densities in Niedernjesa in the topsoil compared to the subsoil, as precipitation in Niedernjesa was clearly above average.

Cover crop effects on sugar beet aboveground biomass

In an earlier study, radish was found to increase early sugar beet aboveground biomass by May by 50% when averaged over both sites as well as unfertilized and optimally fertilized conditions, while increases after oat and vetch were lower and non-significant (Grunwald et al. 2023). In this study, for Hevensen, positive effects from all three cover crops were partially still found in June and July for leaf biomass. In August, however, no differences among the treatments were detected and in September a negative effect of oat and radish compared to fallow was found for leaf biomass. Taproot biomass did not differ significantly between the cover crop treatments at any sampling date including harvest, similarly to sugar yield. Thus, the slight advantages for sugar beet grown after cover crops seen for leaf development in the beginning of the growing season, possibly due to an improved soil structure (Grunwald et al. 2023), disappeared with time and did not lead to any benefit in yield, but in fact rather to an (insignificant) reduction. This fits well to results by Koch et al. (2022) who, for the unfertilized plots in this trial, similarly found no benefit of vetch regarding sugar beet N uptake and sugar yield and even lower values after oat and radish compared to fallow. While the initial benefits found in this study might be explained with an increased N supply after the cover crops compared to fallow, as found by

Koch et al. (2022), N supply in the latter half of the vegetation period was disproportionately lower after the cover crops, leading to an overall lower N supply compared to fallow (Koch et al. 2022). This possibly caused, but was apparently not ameliorated by, the increased root growth of sugar beet. Thus, for this site, possible positive effects of cover crops regarding soil structure and root growth conditions were apparently superimposed by the slow mineralization of the cover crop N.

In Niedernjesa, sugar beet leaf biomass did not show significant differences between fallow, oat and vetch in June and July, only after oil radish a higher biomass was found. This effect might be related to the better N supply in an early stage due to the higher N fertilization after radish, possibly before the (high) N mineralization at this site could level N supply for all treatments; however, as discussed above, we would rather assume that this is a positive effect of the improved soil structure due to high belowground biomass of radish in this year. The increased root network might rather be a further result of the improved crop growth than its cause, as neither nutrient nor noteworthy water limitation might have occurred at this stage.

From August on, leaf and taproot biomass were partially higher after all three cover crops compared to fallow, yet at harvest no significant positive effects were found for taproot biomass or sugar yield. As N supply was exceptionally high here, the drawbacks of cover crop cultivation were apparently of no importance, but rather only the positive effects regarding soil structure (Grunwald et al. 2023). However, differences in root length density of sugar beet after the cover crop treatments do not seem to have played a causal role in the aboveground biomass differences to fallow, as the direction of the changes was different between the study years, while in both years increases in sugar beet root length density were found.

Similar to our study, differences in sugar beet root length density were not correlated to yield in the studies of Windt and Märländer (1994), who concluded that a high root length density is not a prerequisite for a high yield, and Fitters et al. (2022), who speculated that there might be a certain trade-off between the investment in a larger root system and the actual gains of this process for plant growth. In both cases, as in our study, no severe drought stress was found. Under drought conditions, a larger root network might prove to be more beneficial for yield formation. Under non-limiting conditions, however, given that sugar beet may get 80% of its water uptake from the upper 30 cm of soil despite roots in lower layers (Brown and Biscoe 1985), a smaller root network might be sufficient (Fitters et al. 2017).

However, the soil structural improvements by the cover crops found in a previous study on the field (Grunwald et al. 2023) might, in the absence of N limitations caused by cover cropping, be beneficial for sugar beet growth via another pathway. Koch (2009) found positive effects of an improved soil structure on sugar beet taproot yield, particularly in the second half of the growing period (July to September) in a study on a soil similar to the ones studied here comparing differences in soil structure caused by variations in tillage and wheeling treatments. As an unfavorable soil structure might impede sugar beet taproot growth physically (Koch 2009), an improvement in soil structural parameters could increase sugar beet yield which constitutes a possible advantage of cover cropping specifically for sugar beet or other root crops, beyond effects on water and nutrient supply. Nonetheless, as the differences between the cover crop treatments and fallow were non-significant, also in Niedernjesa without an N limitation, this effect was apparently rather small in our trials. This might have been due to a lack of soil compaction at the study sites, as discussed above. Thus, cover crops might indeed be more favorable than found here in more limiting situations regarding soil compaction.

Cover crop effects on carbon input into the soil by sugar beet cultivation

Increasing sugar beet root biomass by agronomic measures might affect the evaluation of sugar beet cultivation regarding soil carbon dynamics and thus its contribution to climate change. The main disadvantage of sugar beet or, more generally, root and tuber crops in comparison to cereals or most other crops in this regard is the low amount of fine root biomass remaining in soil after harvest (Bolinder et al. 2015; Poeplau et al. 2021), as carbon from this fraction of plant residues is more likely to be stabilized in soil for a longer period than carbon from aboveground crop residues (Kätterer et al. 2011). The increases of this fraction in sugar beet by July through cover crop cultivation partially found in this study, in particular after radish, are thus also of high interest beyond possible effects on sugar beet growth and yield. Moreover, when comparing cover crops to a fallow control, carbon from the cover crop above- and belowground biomass remaining in the field is a further additional input.

In our study, the data for sugar beet residue C input have to be seen as minimum values as the belowground data are from a sampling date in July. Thus, final biomass inputs via this pathway could indeed be higher. Concerning aboveground inputs, the September sampling date seemed more suitable than the harvest date, as sugar beet leaf biomass can be expected to reach its maximum sometime before harvest, as can also be seen in most cases in our study. Overall, the choice of sampling dates may not affect the general finding of this study that, while sugar beet root biomass could be increased by the cover crops, the additional carbon input by the cover crop biomass itself and, at least in Niedernjesa, by an increased sugar beet leaf biomass were of much higher importance for the overall C input by sugar beet cultivation preceded by a cover crop. Still, aboveground biomass carbon may be stabilized to a lower extent in the soil (Kätterer et al. 2011), which may be even more pronounced for sugar beet than for other crops (Grunwald et al. 2021) and also for cover crops due to their low C:N ratios (Koch et al. 2022). However, the gains in sugar beet root biomass after cover crops are considerably lower than the cover crop root biomass alone. Thus, overall, cover crops significantly increase the carbon input in sugar beet cultivation by between 47 and 85%, yet additional sugar beet fine root biomass is of a low importance in this calculation.

Conclusion

Cover crops, particularly those with a large above- and belowground biomass accumulation, may increase the root length density and root biomass of the subsequent sugar beet crop by July. This increase was not directly associated with a corresponding effect on leaf or taproot biomass, however, both leaf and taproot biomass may be increased by cover crop cultivation, possibly by the same causal effects that lead to an increase in sugar beet root length density i.e., an improved soil structure. Beyond these possible plant growth advantages, further benefits may arise from enhanced input of organic matter into the soil, both from sugar beet residues and from the cover crop itself. Further studies are needed to investigate potential physiological benefits for sugar beet arising from an increased root system under more limiting conditions, in particular drought. Concerning potential carbon farming approaches in sugar beet cultivation, the input of crop residues from cover crops as well as sugar beet into the soil should be further investigated under diverse growing conditions.

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Author contributions H-JK specified the research questions and designed the experimental setup and measurements. DG performed the statistical evaluation. DG developed the concept of the manuscript, prepared figures and tables, and wrote a draft, which was repeatedly revised by H-JK. Both authors contributed to the article and approved the submitted version.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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