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Wood fiber and green manure as soil improvers in vegetable production

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ABSTRACT

Introducing sustainable management practices to vegetable farming is necessary for maintaining and enhancing the quality of soil under intensive cultivation. Especially measures to increase organic matter are favorable, but their integration requires research. Clean organic inputs in the form of fiber sludge from the pulp industry or green manure grown on site are promising alternatives for improving vegetable-growing soils. These inputs may, however, alter the nitrogen (N) dynamics of the system and challenge fertilization optimization. In this study, the effects of (1) fiber sludge, (2) composted fiber sludge with broiler manure, and (3) green manure on crop growth, N uptake and soil total carbon (C) and available N contents and water retention were evaluated in a three-year field experiment to assess possibilities of integrating soil-improving measures in high-value cropping. The study involved increasing N fertilizer rates in open field vegetable production. Onions (*Allium cepa*) grown in the first year following the treatments reflected increased N availability derived from the residual N of the fiber sludge-broiler manure and green manure treatments, but the effect was not consistent over time and between N rates. Minor accumulation of nitrate–N in the subsoil indicated risk of N leaching following green manuring. No soil improving treatment-induced effects were discernible in the soil or crop N in white cabbage (*Brassica oleracea convar. Capitata var. Alba*) grown on the second vegetable season. Neither soil water retention characteristics nor soil C stocks were affected by the one-time soil improving. For measurable effects, repeated treatments would be needed.

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Cabbages; carbon; nitrogen availability; onion; plant available water

Introduction

Vegetables are essential components of a diverse and nutritious diet, therefore advancing both food security and human health requires increasing their production and consumption (Keatinge et al. 2011; Schreinemachers, Simmons, and Wopereis 2018). Intensive commercial vegetable farming is, however, stressful to the environment and the land under cultivation due to abundant fertilizer and pesticide use, often excessive irrigation, heavy field traffic, and frequent tillage (McPhee et al. 2015; Thompson et al. 2020). Chan et al. (2007) compared long-term vegetable fields (>10 years) to adjacent unfarmed reference sites in Australia and found that the vegetable soils had lost a considerable amount of carbon (C) in the surface layer and exhibited low structural stability. In an earlier investigation by Haynes and Tregurtha (1999) in New Zealand,

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vegetable production was likewise connected to a decline in soil organic C and further decreases in microbial biomass, earthworm numbers, and aggregate stability and porosity. Similar soil degradation under vegetable cultivation has also been reported by eg Wang et al. (2014) in China, Alliaume et al. (2013) in Uruguay, and Figuerêdo et al. (2020) in Brazil. In the long term, degradation of soil impairs crop productivity, exacerbates the environmental load of the production, and reduces resilience, increasing vulnerability to climate change (N. P. Webb et al. 2017). Consequently, adopting management practices sustaining and enhancing soil quality in vegetable cultivation is essential.

Amending vegetable-growing soils with organic inputs has been shown to be a feasible option in improving the soil physical, chemical, and biological conditions (Norris and Congreves 2018). The positive effects derive from the central role of organic matter in soil structure formation and stabilization which affects water retention and aeration properties, as well as organic matter serving as a reservoir of nutrients and energy for soil biological activities (Lal 2020; Obalum et al. 2017). An extensive range of organic side streams, such as crop residues, food waste, bone meal, animal manures, and industrial wastes can be used as soil improvers (Babla et al. 2022). Among the potential materials for adding organic matter back into the soil, primary sludge from the pulp industry, consisting mainly of short-chain cellulose fibers, is attractive in vegetable production due to its high organic C content combined with a low amount of nutrients and low toxicity (Räty et al. 2023; Turner, Wheeler, and Oliver 2022) as well as its capability to increase soil microbial activity and reduce soil erosion and related nutrient loss (Rasa et al. 2021).

In addition to external organic amendments, incorporating plant material grown on-site into the soil, i.e. green manuring, is an option for increasing the C input in the rotation (Fageria 2007). Legumes are often used in green manuring due to their supply of biologically fixed nitrogen (N), but the selection of suitable non-legumes and mixtures of legumes and non-legumes is extensive and the choice depends on the overall targets of the measure (Cherr, Scholberg, and McSorley 2006). In addition to the C and N supply and the consequent increase in biological activity, green manuring can provide additional benefits such as erosion reduction and improved pest and weed control (Cherr, Scholberg, and McSorley 2006; Rudisill et al. 2015). In vegetable production, avoiding excessive phosphorus (P) loading, along with microbial and chemical contamination are advantages of green manures compared to many external organic amendments (Goss, Tubeileh, and Goorahoo 2013).

In high-value vegetable crop production, ensuring adequate N supply is emphasized to maintain crop yields, while excessive N fertilization must be avoided to prevent losses in product quality and environmental pollution through nitrate (NO_3^-) leaching (Tei et al. 2020). The use of soil-improving materials or green manure in vegetable-containing rotations may challenge the optimization of fertilization due to uncertainty in the amount and timing of N release from the amendments. The degradation of primary sludge with a high C:N ratio tends to temporarily consume N through immobilization in microbial biomass, followed by a subsequent gradual release (Rasa et al. 2021; Räty et al. 2023). The mineralization of N from green manures, or conversely, immobilization, depends on the chemical composition of the plant material and thus varies with plant species and the developmental stage of the plant (Chaves et al. 2004; Lynge et al. 2023).

Initially, this study was motivated by the emerging concerns about soil health among the food processing industry and vegetable farmers, as well as by a knowledge gap related to the integration of soil-improving measures in intensive high-value crop production systems. The specific objective of the study was to evaluate the effect of fiber sludge (FS), composted fiber sludge supplemented with broiler manure (FS+BM), and green manure (GM) as soil-improving treatments on soil organic C contents, soil water retention capacity, crop growth, and N availability in open-field vegetable production systems. Onions were grown in the first and cabbage in the second year following the soil amendment treatments, with three increasing mineral-N fertilization rates.

Materials and methods

Soil amendment materials

The fiber sludge, originating from the pre-clarification of cardboard process waters, was provided by Soilfood Ltd. This nutrient-poor, cellulose-based organic side stream was derived from Stora Enso's mill located in Imatra, southeastern Finland. A commercially available soil improver prepared from composted wood fiber and broiler manure (Pehtoorin Ehta) was provided by Humuspehtoori Ltd. The selected properties of the materials are presented in Table 1. The amendments were applied as received from the commercial suppliers.

Green manure

The green manure used was a mixture of vetches, cereals, and ryegrass (*Vicia sativa* cv. Ebena 20% of total seed weight, *Vicia sativa* cv. Alexandros 10%, *Vicia villosa* cv. Rea 10%, *Triticosecale* cv. Somtri 15%, *Avena sativa* cv. Matty 15%, *Hordeum vulgare* cv. Armas 10%, *Triticum aestivum* cv. Lennox 10%, *Secale cereale* cv. Sangaste 5%, *Lolium multiflorum* cv. Meroa 5%). Seeding rate was 120 kg ha^{-1}.

Field experiment

A three-year field experiment was conducted on a fine sand soil (81.5% sand, 9% silt, and 9.5% clay) at Luke's experimental station in Piikkiö, southwest Finland. At the beginning of the experiment in April 2021, the soil pH was 6.8, total C content approximately 2% and easily available N content 10.9 mg kg^{-1} (2.5 mg ammonium–N (NH_4–N) kg^{-1}, 3.2 mg NO_3–N kg^{-1}, and 5.2 mg organic N kg^{-1}).

In 2021, four soil improvement treatments and a control were randomized in a complete block design with four blocks (Table 2). Fiber sludge and fiber sludge with manure were applied with the rate of 40 tons per hectare (fresh weight). The total inputs of C, N, P and potassium (K) from the fiber sludge were 4500 kg C ha^{-1}, 4 kg N ha^{-1}, 0.2 kg P ha^{-1}, and 1.5 kg K ha^{-1}. The corresponding values for fiber sludge with broiler manure were 4100 kg C ha^{-1}, 110 kg N ha^{-1}, 22 kg P ha^{-1}, and 50 kg K ha^{-1}. Nitrogen immobilization by the nutrient-poor fiber was compensated by adding 30 kg ha^{-1} of mineral N (YaraBela Suomensalpietari) on the same date. Fiber sludge and N fertilizer were mixed into the soil with a cultivator on 29 April 2021. Fiber-manure mixture was added in a similar manner on 31 May 2021. Oats (cv. Taika, seeding rate 200 kg ha^{-1}) and green manure were sown to the plots on the 1^{st} of June 2021. Plot size was 7.5 m x 8 m. Oats were sprayed twice to control aphids (tau-fluvalinate, Mavrik 2 F, 0.2 l ha^{-1}, Adama

Table 1. Selected properties[a] of the soil amendment materials applied in the field experiment (Suojala-Ahlfors et al. 2024).

	Fiber sludge	Fiber sludge + broiler manure
Moisture (%)	74	73
Ash (% dm)	7.2	31
pH	7.5	7.1
Electrical conductivity (mS cm^{-1})	87	1157
Total C (% dm)	44	38
Total N (% dm)	0.04	1.0
Water extractable N (% tot N)	24	22
Total P (g kg^{-1} dm)	0.02	2.0
Total K (g kg^{-1} dm)	0.15	4.9
Total Mg (g kg^{-1} dm)	0.38	2.3
Total Cd (µg kg^{-1} dm)	7	31

[a]Moisture in 105 °C, ash in 550 °C, pH (EN13037) and EC (EN 13038) from 1:5 water extraction, total N with Kjeldahl digestion and distillation, total C with Dumas method, total, extractable N with 1:5 (v/v) water extraction and Skalar San++ analyzer, P, K, Mg and Cd with aqua regia extraction and ICP-OES (P, K, Mg) or ICP-MS (Cd) determination.

Table 2. Soil improvement treatments in 2021.

Treatment abbreviation	Crop	Soil amendment: Material	Soil amendment: Rate (t dm ha^{-1})	Soil amendment: Date of application	Extra mineral N fertilization (kg ha^{-1})	Mineral N fertilization on sowing date (kg ha^{-1})
C (control)	Oats					80
FS	Oats	Fiber sludge	10.2	29 April	30	80
FS+BM	Oats	Fiber sludge + broiler manure	10.8	31 May		50
GM	Green manure					30
FS+GM	Green manure	Fiber sludge	10.2	29 April	30	30

Ltd, and flonicamid, Teppeki, 0.12 kg ha^{-1}, Belchim Crop Protection, on 23 June). No chemical herbicides were used. Oats were threshed on 31st of August and green manure was crushed on 1st of September. The plant material, including oats straw, was left on soil surface until the field site was plowed next spring.

In 2022, the main plots of soil improvement treatments (Table 2) were divided into three subplots (size 2.5 m x 8 m), in which three mineral N application rates were randomized: 0, 50, and 100 kg N ha^{-1}. All treatments received 10 kg ha^{-1} of P and 123 kg ha^{-1} of K (plus other macro- and micronutrients according to soil analysis) in mineral fertilizers, which were manually applied to the plots and incorporated into the soil. In the N100 treatment, the N application was split with 70 kg ha^{-1} of N applied in spring and 30 kg ha^{-1} in late June.

Onion (cv. Setton) was planted in the plots from 17 to 19 May 2022. Each plot had a four-row bed (row spacing was 30 cm and bed spacing 60 cm) with one border row on each side of the bed. Onion sets were planted in the rows at a 6-cm spacing (17 plants per meter of row). Weeds were controlled using pyridate (Lentagran WP, Belchim Crop Protection) on the 6 June and by a pyridate-aclonifen-metamitron mixture (Lentagran WP, Belchim Crop Protection; Fenix, Bayer Crop Science; Goltix 70 WG, Adama Ltd.) on the 13 June.

In 2023, white cabbage was cultivated in the same plots maintaining the sequence of N application rates in the subplots. The N application rates were, however, higher than previously used for onion. The N rates applied for cabbage were 50, 125, and 200 kg ha^{-1}. Cabbage transplants (cv. Lennox) were planted from 15 to 16 May. The planting distance was 0.6 m $\times$ 0.6 m, resulting in 52 plants per plot. The two higher N rates were split between spring applications (75 and 100 kg ha^{-1}, respectively) and summer applications (1×50 kg ha^{-1} and 2×50 kg ha^{-1}, respectively). Spring fertilization was done on 12 May and in addition to N, it included 10 kg ha^{-1} of P and 200 kg ha^{-1} of K, along with other macro- and micronutrients according to soil analysis. Mineral fertilizers were spread manually onto the plots and incorporated into the soil.

The cabbage planting was covered with insect netting (mesh size 0.8 mm) from planting to harvest, but the net was removed three times during the growing season for manual weeding, fertilization and plant sampling. Three days prior to planting, the herbicide napropamide (Devrinol 450 SC) was sprayed and incorporated into the soil. A second herbicide treatment was applied by spraying the planting with pyridate (Lentagran WP, Belchim Crop Protection) on 31 May.

Plant and soil sampling

Plant growth was monitored each year by sampling the plants two to three times during the season and at harvest. The size of the sampled area in each plot was 0.5 m^2 in oats and green manure, 0.45 m^2 in onion (approximately 20 plants), and 0.72 m^2 (2 plants) in cabbage. The collected plant material was weighed, oven-dried at 60 °C, and stored for further analysis. Oat and green manure samples were cut at ground level. At the first sampling date, the biomass of onion and cabbage plants was measured as total plant weight (above-ground parts), but in later samplings, bulbs and leaves in onion, and heads and outer leaves in cabbage were separated.

At harvest, the yield was measured from a 0.5 m^2 area in green manure, in 12 m^2 in oats (by combine harvester), in 6 m^2 in onion, and in 3.6 m^2 in white cabbage. In onion and white cabbage, separate plant samples were taken for N analysis at harvest. Harvest dates were 31 August 2021, 17 August 2022, and 18 September 2023.

Onion yield was weighed after drying the bulbs in a ventilated storage room at 25 °C. Total and marketable yield was measured for onion and white cabbage. Onion yield was also subjected to a storage test, by keeping the bulbs at 0–1 °C for five months, after which the onions were graded into marketable and unmarketable (diseased) classes.

Composite soil samples (from 0 to 20 cm and 20–40 cm layers) were taken in April 2021 before soil amendments were applied (1 combined sample from each experimental block) and thereafter they were taken each year at the end of the growing season in September-October and at the beginning of the season in April-May by bulking 8 subsamples collected by an auger of 3 cm diameter. In autumn 2021 and spring 2022, the samples were taken from each main plot of the soil improvement treatments (Table 2). In later samplings, 0–20 cm samples were taken from each subplot and 20–40 cm samples were taken only from the subplots with the middle N fertilization (N50 for onion and N125 for cabbage). These samples were stored at −20 °C until analysis. In addition, four undisturbed soil samples were collected in approximately 200 cm^3 metal cylinders at a depth of 2.5–7.5 cm from each plot in early September 2021 and from each middle-level N subplot at the end of August 2022.

Plant and soil analyses

The composite soil samples were extracted immediately after thawing with 2 M potassium chloride (1:2.5 (w:v) for 2 h). The extractants were analyzed colorimetrically using a Skalar San^{++} autoanalyzer for inorganic NO_3–N and NH_4–N. In addition, the amount of total easily-available N was measured after oxidative digestion of the extracts. The difference between total available N and inorganic N was taken to represent organic N.

The composite samples taken from the topsoil (0–20 cm) at the end of the experiment in October 2023 were size and density fractionated immediately after thawing to assess the effects of the soil improving treatments on soil C stocks as in Keskinen et al. (2024). In brief, fresh soil samples (50 g each) were wet-sieved to obtain size fractions of $<$ 0.063 mm and 0.063–2 mm. Thereafter, the coarser fraction was density-separated in sodium polytungstate adjusted to a 1.8 g cm^{-3} density to separate the light particulate organic C (POC) from the heavy mineral-associated C (MOC). Finally, the total C content of each of the three fractions was analyzed by dry combustion using Leco 628 CHN Determinator.

The undisturbed soil samples were subjected to analysis of soil water retention capacity as in Räty et al. (2023) by equilibrating the soils successively at suction pressures of 0.1, 0.3, 1.0, 3.2, 10, 32, 100, 316, 1585, and 39,811 kPa. The first two equilibrations were conducted in a water-containing plastic box, and the next six on ceramic plates in pressure extractors. The last two matric potentials were achieved in desiccators with saturated solutions of ammonium oxalate and sodium chloride, respectively, using small (1 g) sieved soil samples. After each step, the samples were weighed, and their shrinkage was measured. Finally, the volumetric water content at each matric potential was calculated. The following soil moisture characteristics were calculated from the data, based on water extracted between the suction pressures: drainable water, 0.1–10 kPa (DW); easily plant-available water, 10–316 kPa (EPAW); and plant available-water, 10–1600 kPa (PAW).

Statistical analysis

The fixed effects of soil improvement treatment (5 classes) on the characteristics of soil, harvested plants and stored plants (onion and white cabbage) were studied. Nitrogen fertilization (3 classes) and soil depth (2 classes) were possible additional fixed effects. Statistical analyses were based on randomized blocks or split-plot design in four blocks, depending on the study year and target (soil, harvested plants, or stored plants). Measured characteristics were analyzed separately for five study seasons (2021 autumn – 2023 autumn), except for stored plants, where the analyses were performed for the 2022 onion harvest.

Generalized linear mixed models were used in the analyses to account for the distribution, correlation, and variance of observations for each analyzed characteristic (Gbur et al. 2012). Normal distribution was assumed for most of the characteristics (some after transformation), while beta distribution was used for proportions in the storage data. The necessary fixed-effect interactions and random effects were included in the models.

The Bonferroni method (with a significance level of 0.05) was used in pairwise comparisons of model-estimated class means (which were back-transformed to the original scale for meaningful interpretation with transformed or beta distributed characteristics). The statistical analyses were performed using the GLIMMIX procedure of SAS software (version 9.4).

Results

Effects of soil improving treatments on crop growth and N uptake

Green manure and oats combined to fiber sludge amendment (2021)

The fiber sludge amendment either alone or combined with broiler manure had no significant effect on the accumulation of above-ground oat biomass (Figure 1a) nor on the N uptake into the leaves, straw, and grains of oats (Figure 1b). In the green manure, a small negative effect of the spring-applied fiber sludge was detected at the end of the growing season (Aug 31) in both above-ground plant biomass and its N content. By mid-August, the green manure, consisting mostly of leguminous crops (61% ±3.6% of dry mass in mid-August sampling), contained roughly double the amount of N found in the oats, and the difference between the crops further increased in the final harvest. In above-ground biomass, the green manure exceeded oat biomass only at the end of the season, when the oats biomass showed decline due to withering of the leaves.

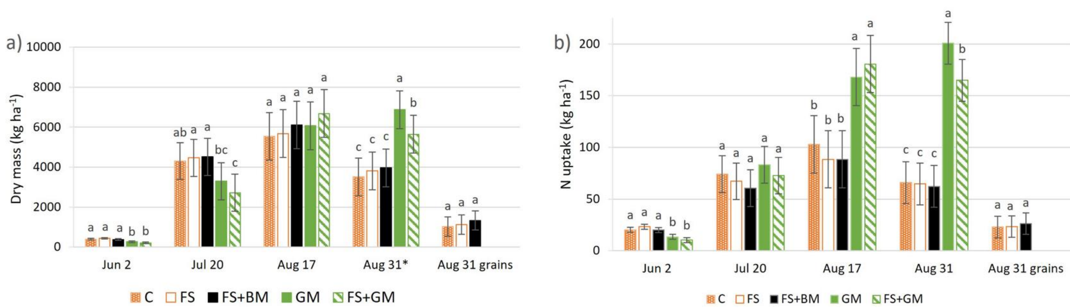

Figure 1. Above-ground plant dry biomass (a) and nitrogen content (b) of oats (C, FS, FS+BM) and green manure (GM, FS+GM) during the growing season of 2021. Soils were amended with fiber sludge prior to sowing in FS and FS+GM, while FS+BM received fiber sludge combined with broiler manure. The values are mean estimates with 95% confidence intervals ($n = 4$). Significant differences ($p \leq .05$) between treatments within sampling times are denoted by different letters. *In treatments C, FS and FS+BM, the husk is not included, causing an underestimation of approximately 100 kg ha^{-1} in the total biomass value.

Onion (2022)

The effects of the previous year's management (Table 2) on the growth and N uptake of onions were overall inconsistent and seemed to vary during the growing season and between the different N application rates (Figures 2a–f). The additional N (on average approximately 180 kg ha^{-1}) introduced in the green manure crop incorporated in the soil (Figure 1b) tended to result in increased biomass accumulation and N uptake in the non-N-fertilized crop, especially when combined with fiber sludge amendment, though significant differences were mainly recorded only in the July sampling. In treatments fertilized with mineral N (N50 and N100), this systematic trend was lost. The main effect of the annual N application rate was clear: N0 (no N application)

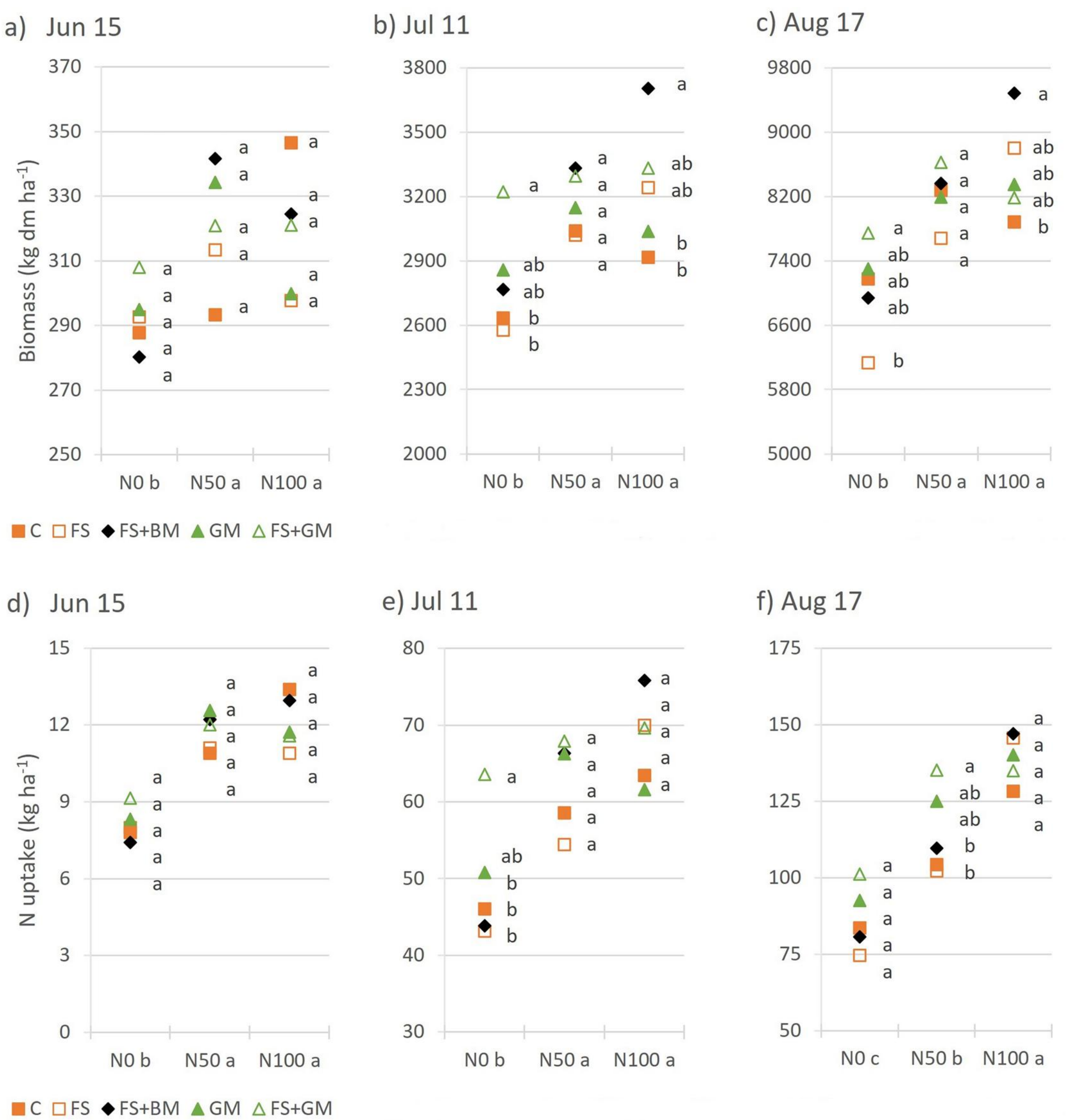

Figure 2. Above-ground dry biomass (a–c) and nitrogen content (d–f) of the onion crop at various dates following previous soil improving treatments: C control (oats), FS fiber sludge amendment (oats), FS+BM fiber sludge combined with broiler manure (oats), GM green manure, and FS+GM green manure with fiber sludge. The values are mean estimates ($n = 4$). Significant differences ($p \leq .05$) between soil improving treatments within each N rate and sampling time are denoted by different letters beside the symbols, while differences between N rates within the same sampling time are shown with different letters beside the rate captions. Note the variable scales of the vertical axes used for clarity.

produced significantly lower above-ground onion biomass and lower N uptake than treatments with 50 kg N ha^{-1} or 100 kg N ha^{-1} additions. No benefit in produced dry mass was obtained when increasing the N rate from 50 to 100 kg ha^{-1}, though the additional N significantly increased the N content in the crop.

Considering the marketable onion yield, significant differences between the previous soil improving treatments were observed only at the highest N application rate (Table 3). The apparent poorer performance of the green manure treatment was not, however, consistent with the dry mass yields (Figure 2c) determined from different samples. The yield quality was overall good and not affected by the treatments, as the percentage of marketable yield was greater than 96% of the total yield throughout. Neither the soil amendments nor the N rate did affect the storage ability of the yield: after five months of cold storage, the proportion of healthy bulbs was greater than 97% in all treatments. Differences in the marketable yield between N fertilization rates were consistent with the dry mass yields.

White cabbage (2023)

Previous soil improving treatments from 2021 had no effect on the accumulation of biomass (Supplementary Figure 1 a–d) or on the N uptake in aboveground parts of white cabbage grown in 2023 (Supplementary Figure 1e–h). The soil improving treatments also had no effect on the marketable yield (Table 3). The proportion of marketable yield relative to the total yield was generally high (between 89 and 100%). Unmarketable heads were mainly caused by sporadic damage from *Lygus rugulipennis*, which affected the growing point of the plant and resulted in multiple heads per plant. In contrast, the annual N fertilization rates had a significant effect on the total dry mass production, N uptake, and marketable cabbage yield. However, even with the lowest N fertilizer rate, 50 kg ha^{-1}, white cabbage produced a considerable marketable yield of 60 tonnes ha^{-1}. When the N fertilizer rate increased from 125 to 200 kg ha^{-1}, the marketable yield increased by an average of 6 700 kg ha^{-1} but the difference between the two treatments was not statistically significant. N uptake in cabbage responded even more clearly to the N fertilizer rate, rising from an average of 155 kg ha^{-1} in N50 to 291 kg ha^{-1} in N200. These numbers emphasize the high inherent N supply of the soil, which was also apparent in the N uptake of the non-N-fertilized onions in the previous year (N0, Figure 2f).

Effects of the soil improving treatments on soil easily available nitrogen

At all six assessed time points, the total amount of easily available N extracted from the soil with potassium chloride was moderate, ranging roughly between 5 and 20 mg N kg^{-1} soil, which converts to approximately 10–50 kg N ha^{-1} in the 20-cm thick layers with the average soil bulk density of 1.3 g cm^{-3} obtained from the undisturbed cylinder samples. At the end of the growing season 2021 encompassing the soil improving measures, green manuring (GM and FS+GM)

Table 3. Marketable yield (kg ha^{-1}) of onions (2022) and white cabbage (2023) at trade moisture after soil improving treatments carried out in 2021.

	Onion			White cabbage		
Treatment	N0 (B)	N50 (A)	N100 (A)	N50 (B)	N125 (A)	N200 (A)
C	39,521 a	47,923 a	50,837 abc	61,028 a	80,438 a	81,361 a
FS	37,639 a	48,633 a	52,722 ab	66,319 a	91,389 a	97,917 a
FS+BM	39,598 a	52,210 a	54,958 a	60,194 a	83,924 a	93,347 a
GM	38,624 a	47,505 a	44,412 c	56,007 a	89,840 a	86,813 a
FS+GM	44,328 a	49,706 a	46,602 bc	55,736 a	77,458 a	97,201 a

Notes: The values are mean estimates ($n = 4$). Significant differences ($p \leq .05$) between soil improving treatments within each N rate are denoted with lowercase letters and differences between N rates within crop are shown in parentheses with uppercase letters.

stood out from the other treatments with higher topsoil total easily available N contents attributable to a higher amount (approximately 15 kg N ha^{-1}) of NO_3–N (Figure 3a). However, the effect did not extend to the subsoil which exhibited overall lower N contents (Figure 3b).

Elevated soil NO_3–N contents in the green manure treatments were still discernible in the topsoil by the following spring (May 2022, Figure 3c), and similarly to the previous sampling, no differences between treatments were seen in the subsoil (Figure 3d). In autumn 2022, after the onion crop, there was an increasing trend in topsoil NO_3–N content from C to FS+GM, but the difference was significant only between C and FS+GM (Figure 3e). In the subsoil, the green manure treatments (GM and FS+GM) maintained slightly higher NO_3–N content compared to the C and FS treatments (Figure 3f). No soil improving treatment effects were recorded in the 2023 samplings (Figures 3g–j).

Regarding the increasing N fertilization rates applied in subplots during 2022 and 2023, the effects on residual available soil N remained generally small. The highest level of N100 significantly increased the soil NO_3–N content in the 0–20 cm surface layer after the onion harvest in 2022 from approximately 13 kg ha^{-1} to 21 kg ha^{-1} averaged over the soil improving treatments. In spring 2023, no differences between the fertilizer application rates were recorded in the soil. After the cabbage crop in 2023, only the soil NO_3–N levels differed significantly between all N application rates, but the differences were of no practical significance as the NO_3–N content ranged between 1 and 2 kg N ha^{-1} (0–20 cm).

Effects of the soil improving treatments on soil water retention capacity

Soil water retention characteristics were measured after the first and second growing seasons. No statistically significant differences between the treatments were found (Table 4). The soil porosity varied between 49 and 55% and was slightly higher in the second growing year. In line with that, drainable water showed higher values in 2022 than in 2021. The amount of plant-available water varied from 19.9% to 22.6% (vol.), roughly half of that in easily plant-available form.

Effects of the soil improving treatments on soil C

At the end of the experiment, two growing seasons after the implementation of the soil improving treatments, no significant differences were observed in soil total C content (sum of the three fractions) between the treatments (total C 1.7 ± 0.2%, $p = .2$). The separate fractions of POC and MOC (<0.063 mm and 0.063–2 mm summed) did not differ between the treatments. The majority of the soil C resided in the MOC fractions; approximately 82% in the < 0.063 mm and 9% in the 0.063–2 mm size class, respectively, with the share of POC being approximately 8%.

Discussion

Effects of soil improving on crop yields and need of N fertilization

Soil application of organic materials high in C and low in N, like the current fiber sludge, is well known to induce transient N immobilization, as N is bound into the cellular structures of the decomposing organisms (Camberato et al. 2006; Räty et al. 2023). To avoid excess plant-microbial competition over N and the consequent reduction in crop growth, fiber sludge is recommended to be spread in the autumn after harvest. In the current study, spring application was required due to a limitation in the project duration. An adequate N supply for the crops following the amendment can be secured by supporting the N demand of the growing decomposer community with additional N (Camberato et al. 2006). In the current study, an additional 30 kg of mineral N per hectare prevented negative growth effects in oats. This outcome was, however,

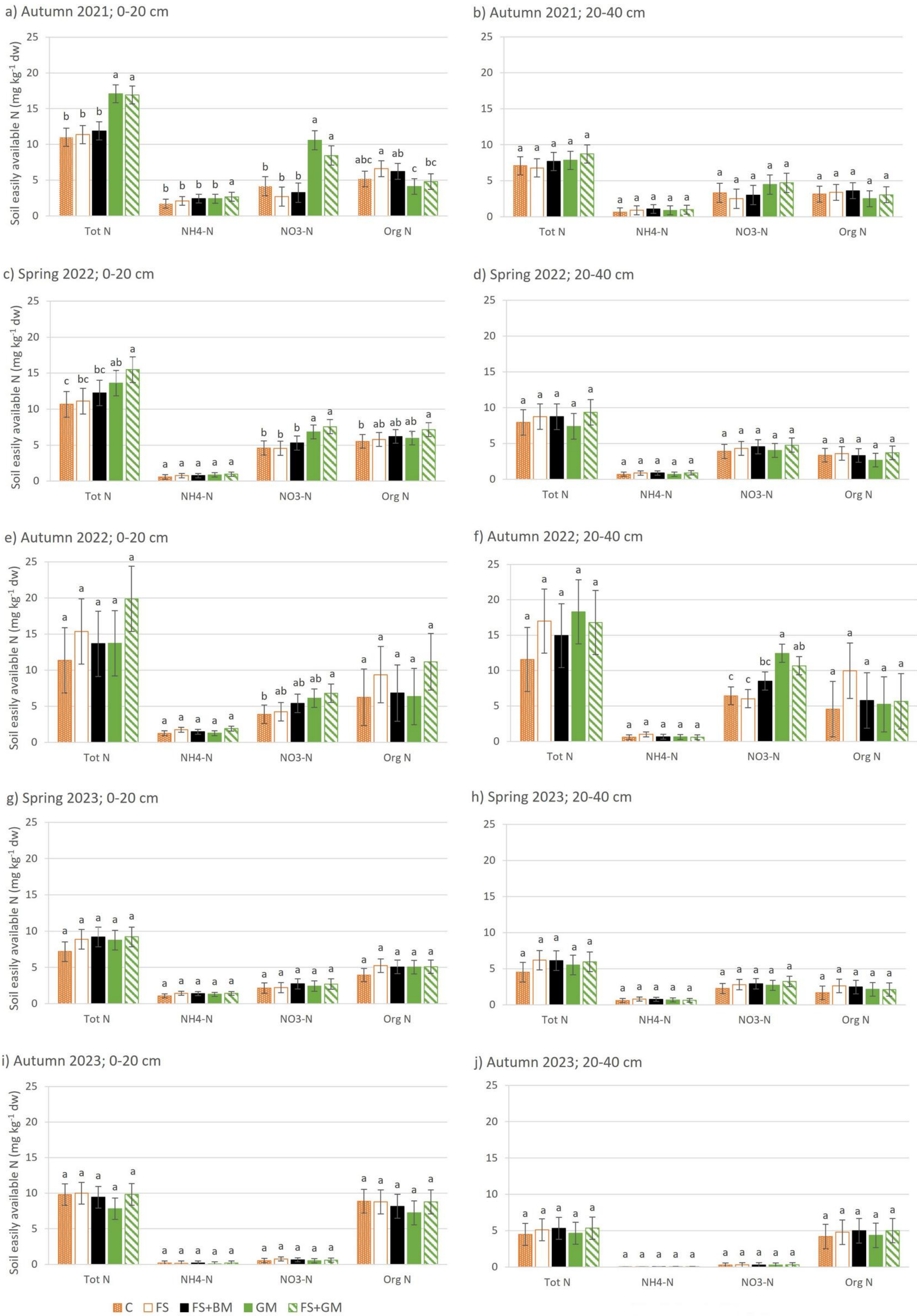

Figure 3. (a–j) Total easily available (KCl-extractable) N and its speciation into NH_4–N, NO_3–N and organic N in 0–20 cm and 20–40 cm soil layers from autumn 2021 to autumn 2023 in five soil improving treatments conducted in summer 2021: C control (oats), FS fiber sludge amendment (oats), FS+BM fiber sludge combined with broiler manure (oats), GM green manure, FS+GM green manure with fiber sludge. The values are mean estimates of four replicates ± 95% confidence intervals. The data for 2022 and 2023 are from the middle fertilization level. Significant differences at $p < .05$ are marked with different letters within each sampling time, depth, and N species.

Table 4. Soil porosity and other selected water retention characteristics following soil improving treatments carried out in 2021.

	Porosity	PAW	EPAW	DW
		(vol%)		
2021				
C	49.0	20.7	9.2	23.2
FS	51.4	20.9	9.1	24.7
FS+BM	51.7	22.6	9.1	23.3
GM	50.0	21.6	10.3	23.6
FS+GM	51.6	21.9	9.2	25.4
2022				
C	53.2	20.2	9.6	29.8
FS	53.9	20.8	9.6	29.6
FS+BM	54.8	20.0	9.3	31.4
GM	53.9	19.9	9.9	30.7
FS+GM	53.3	20.6	9.8	29.2

Notes: PAW: plant-available water; EPAW: easily plant-available water; DW: drainable water. The values are mean estimates of four replicates. No significant differences ($p \leq .05$) between soil improving treatments within years were observed.

probably influenced by the very dry early part of the growing season, which delayed the decomposition of the sludge typically occurring very rapidly during the first weeks after application (Fierro, Angers, and Beauchamp 2000; Räty et al. 2023). The drought resulted in an overall poor growth and very low oat yield. In August, when the stunted oats were already ripening, the field received rain, which benefited both the growth of the green manure and the decomposing microbes leading to approximately 20% lower above ground plant biomass and N reserves in the fiber sludge-amended green manure treatment in comparison to that grown without fiber sludge. This difference is, however, subject to potential error in the sampling as the tangled mature green manure stand was difficult to collect accurately on an area basis. Considering vegetable production, a small reduction in the yield of the intermediate crop is, however, not critical if benefits can be gained with the main cash crop.

The soil improving treatments done in spring 2021 were assumed to generate very different circumstances regarding residual N availability in the subsequent growing season 2022. The fiber sludge itself practically brought no extra N to the system, but the treatment included an additional mineral N input (30 kg ha^{-1}), which was expected to be immobilized and later released for plant uptake. The fiber sludge – broiler manure combination encompassed approximately 100 kg ha^{-1} of recalcitrant organic N, mineralizable in the long term. The growth and N uptake of oats in this treatment (FS+BM) were equal to those in the control oats (C) that had received 30 kg ha^{-1} more mineral N fertilization. Considering the low proportion of easily available N (approximately 20%) in the fiber sludge – broiler manure product, the organic N reserves were probably partially released already during the first growing season despite the drought. The share of organic N mineralized from manures during the year of application typically ranges from approximately 20 to 50% (Eghball et al. 2002). The green manure biomass incorporated into the soil in the spring 2022 carried an abundant amount of approximately 180 kg N ha^{-1}, releasable for the next crops.

The effects of these residual N reserves on the N fertilization needs of the following growing season in 2022 with vegetables were assessed using increasing N fertilization rates. Despite the computationally high residual N in the treatments FS+BM, GM, and FS+GM, no clear and systematic response was obtained with onion to formulate recommendations for N fertilization adjustments. The patterns of biomass accumulation and N uptake (Figure 2) indicated that the high residual N treatments FS+BM, GM, and FS+GM provided additional N to the crop, but the effect was mostly not statistically discernible. Some additional easily available N was also detected in the soil in the GM treatments. Furthermore, the data suggested that the fiber amendment might enhance the transfer of green manure-bound N but this prospect could not be ascertained in the current study. Synchronizing the release of green manure-bound N with the N needs of the crop is overall challenging, considering the complexity of green manure composition and variable soil and weather conditions (Cherr, Scholberg, and McSorley 2006). Due to its shallow root system, onion may not have been able to exploit the N mineralized and leached to deeper soil layers (Figure 3f; Willumsen and Thorup-Kristensen 2001). Overall, the reported effects of green manure on the yield of the subsequent crops have been somewhat inconsistent and depend on both the crop and the quality of the green manure (eg Ma et al. 2021). Though previous research has shown the recovery of N from green manure by the subsequent crop to be lower than from mineral N fertilizer, ranging from approximately 10–30%, an abundant leguminous green manure has been shown to provide a considerable share of the following crop′s N needs (Janzen et al. 1990; N'Dayegamiye and Tran 2001).

The organic N not released during the application season can be gradually mineralized over several subsequent years, but the residual fertilizer effects are typically small and difficult to measure (J. Webb et al. 2013). The current observation with white cabbage (after the onion year) of no discernible residual green manure fertilizer effect agrees with previous observations by Janzen et al. (1990) and N'Dayegamiye and Tran (2001). The residual N fertilizer effect of organic inputs tends to fade away with time but with repeated applications, the long-term effects can be emphasized (Schröder, Uenk, and Hilhorst 2007). Ultimately, the N not recovered in the crops either ends up stored in the soil recalcitrant organic N pool or is lost to the environment *via* volatilization or leaching, with potentially negative consequences (J. Webb et al. 2013). Regardless of the soil improving treatments, the current study indicated that the higher amounts of mineral N applied to vegetables may be in excess and merely lead to luxury uptake of N. The importance of estimating and accounting for the soil inherent N supply was highlighted (Soinne et al. 2021). Overall, investment in tools for elaborating the N fertilizer rates would be beneficial.

Effects of soil improving on soil quality

Neither a single soil treatment with fiber sludge as such or composted with broiler manure nor green manure growth over one growing season, either solely or combined with fiber sludge amendment, exerted discernible effects on soil water retention capacity at the end of the treatment season or one year later. The same applied to soil C reserves two growing seasons after the treatments. Distinguishing the effects of single soil improvement treatments on soil characteristics is overall difficult due to the often small magnitude of change against the initial status, the wide spatial heterogeneity in soil, and the dynamic nature and transience of the soil processes (Earl et al. 2003; Heil and Schmidhalter 2017).

Against the predominant paradigm, the effect of soil organic C on soil water retention capacity seems to be rather minor (Minasny and McBratney 2018). Yet on sandy soils, the role of organic matter in soil water-holding characteristics is more pronounced than in fine-textured soils (Libohova et al. 2018). On a laboratory scale, Räty et al. (2023) found fiber sludges to increase plant-available water content in coarse mineral soils by 7–33% in comparison to non-amended soils. In an open field, however, this effect was not detected, even though the water content in medium-sized pores showed a positive response to the fiber treatments (Räty et al. 2024). Foley and Cooperband (2002) observed a significant increase in sandy soil water retention only after the reapplication of papermill residuals and noted a decreasing trend in the soil water-holding ability as the amendments decomposed over time.

In laboratory conditions, 30% of the fiber sludge C was respired during a two-month incubation in soil (Räty et al. 2023). Similarly, in field conditions, Fierro, Angers, and Beauchamp (2000) found paper de-inking sludge to decompose rapidly during the first three months with mass loss exceeding 30%, and thereafter degrading at a slower rate, having lost more than half of the initial mass in 16 months. In comparison to wood fibers, the decomposition of fresh plant material, especially the above-ground parts, is faster (Heikkinen, Ketoja, et al. 2021; Puget and Drinkwater 2001). Therefore, even though the C input was roughly equal between the green manure biomass (assuming a shoot to root ratio of 1.3 (Bolinder et al. 2002) and C content of 41% in shoots and 38% in roots (Ma et al. 2018)) and wood fiber amendment, observing an increase in soil C would have been more likely in the fiber treatments. However, tracing small changes in soil C is generally challenging and requires intensive sampling (Heikkinen, Keskinen, et al. 2021). Räty et al. (2024) detected a fiber-sludge amendment-induced increase in topsoil C at the end of the first growing season after application but no longer after the second growing season. Rasa et al. (2021) found no marked effects on soil C after 4 years of fiber-sludge treatments on a clay soil. A later size and density fractionation of soils from these sites revealed an increase in the POC fractions of soils that had received fiber-sludges, but a significant increase in the total C summed over the fractions was detected only in the soils reamended in the fall preceding the spring sampling (Keskinen et al. 2024).

Regardless of the modest effect of a single soil organic amendment addition on the permanent soil organic C stock, the input of C and other nutrients is beneficial for increasing biological activity and nutrient cycling in soil (Rudisill et al. 2015). Legume-containing green manure can transfer significant amounts of biologically fixed N to the following crop (Kebede 2021). The current N uptake in the green manure was comparable to that in the studies by Haas, Brand, and de la Vega (2007) and Stein et al. (2023), which used vetch or vetch-rye mixtures as winter green manure in Germany, where the N uptake of green manure varied between 113 and 185 kg N ha^{-1}. Decomposition and mineralization of N in the autumn or the winter period, with no vegetation cover, can cause harmful leaching of NO_3–N in the coarse-textured and C-poor vegetable soils (Bai et al. 2021). To reduce the risk of N leaching, a mixture of leguminous and non-leguminous species is often advantageous (eg Rosecrance et al. 2000). In the present study, the impact of green manuring on soil mobile N fell upon the NO_3–N pool, but the amount of NO_3–N in the soil at the end of the green manuring season was moderate despite the high total N content bound in the produced biomass incorporated in soil. The slow decomposition of green manure was likely caused by low soil temperatures at the end of the season in northern conditions. The temperature dependence of soil organic matter degradation in Finland has been discussed by Heikkinen et al. (2022). Nevertheless, there is a risk of N leaching during the varying weather conditions prior to the establishment of the following crop next spring. This risk can be reduced by using winter-hardy green manure crops (Willumsen and Thorup-Kristensen 2001). Spring incorporation of green manure can, however, lead to some preemptive competition for soil N with the following vegetable crop due to immobilization of mineral N, especially if the green manure crop has a high C/N ratio (Stein et al. 2023; Willumsen and Thorup-Kristensen 2001). When combining green manure with the use of mineral fertilizers, as in our study, this hindrance can easily be overcome.

The fiber-sludge, in contrast to green manure, is a poor source of N (Table 1), but its decomposition in soil affects N dynamics. The initial rapid mineralization of the readily available C pool in the fiber-sludge typically results in immobilization of N within the cellular components of microbial biomass (Räty et al. 2023). However, during the later decay of the microbial biomass, the immobilized N will be released (Chen et al. 2014). Fiber-sludge could thus serve in transferring easily available N over the winter period, if the application were timed to the fall following the crushing and incorporation of the green manure vegetation.

Conclusion

Soil improving treatments, fiber sludge and fiber sludge-broiler manure amendments, and green manuring were studied in an open-field vegetable rotation to assess their contribution to N management and capacity in improving soil quality. Growth reductions related to initial N immobilization following fiber sludge application were mainly avoided owing to both supplemental N fertilization and dry growing season hindering both plant and microbial growth, as well as fiber sludge decomposition. The data indicated that green manure and fiber-sludge-broiler manure supplied residual N to the subsequent onion crop, but significant differences were observed only to a limited extent. Soil analysis showed the GM treatments to increase the NO_3–N pool thus involving a risk of NO_3–N leaching over two winters following the treatment. However, deeper soil sampling would have been needed to assess potential N leaching losses. No residual effects on plant and soil N persisted into the second vegetable season. Fiber sludge amended green manure tended to produce higher (although not significantly) biomass and N accumulation in the following onion crop compared to green manure without amendments, suggesting that the fiber sludge might serve in transferring N to the next crop. This prospect is worth further study, ideally combining the fiber sludge amendment with the termination of the green manure stand. The study highlighted the need to develop tools for defining site-specific, demand-adjusted N fertilizer rates. The one-time soil improving treatments exerted no discernible effects on soil C stock or water retention properties. Repeated treatments may be needed to reach measurable long-term effectiveness. More research is needed on the suitable interval between treatments and on the cumulative effects on the residual N availability. Overall, repeating the treatments in different growing conditions would allow better generalization of the results.

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Data availability statement

The data will be made available upon request.

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