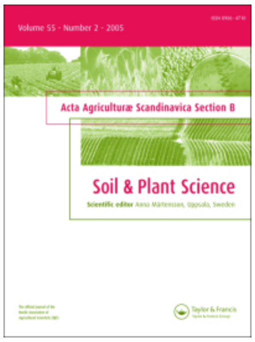

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Effects of organic amendments and cover crops on soil characteristics and potato yields

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ABSTRACT
Intensive potato production may reduce the soil organic matter content (SOM), which may impact several soil functions and increase the incidence of potato diseases. We examined if cover crop and addition of organic materials may counteract these effects. Organic materials were one application of biochar mixed with liquid digestate (BLD); solid digestate (SD); or farmyard manure (FYM); with or without winter rye as cover crop, in a field with regular potato growing. Organic amendment increased SOM, especially for FYM and BLD, while cover crop did not affect SOM. Yet, cover crop increased tuber yields in the second year, and reduced the severity of potato diseases by 10% in post-harvest potatoes in both years. In the second year, the number of marketable potatoes after storage increased by 37% with cover crop. Organic amendments did not affect potato yield or quality, but the proportion of marketable potatoes tended to be higher in the amended soil. By lab incubation, BLD showed the largest potential for SOM storage, up to 32 years, followed by FYM and SD. Cover crops and organic amendments is recommended in potato production, especially for early potatoes where there is sufficient time after harvest to establish a good cover crop.

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Biochar; farmyard manure; liquid digestate; potato disease; potato quality; solid digestate; soil organic matter

Introduction

Potato (*Solanum tuberosum*) is an important staple food crop worldwide. According to FAO estimates, over 359 million metric tons of potatoes were produced worldwide in 2020. In the same year, Norwegian agriculture produced 369000 tons of potatoes. Potatoes are often cultivated in light sandy soils, with use of mineral fertilisers, irrigation, intensive soil tillage and short rotations with other arable crops. In this production system, only small amounts of crop residues are returned to the soil. These agronomic practices may lead to deterioration of overall soil health, resulting in loss of soil organic matter (SOM), reduced water holding capacity, poor soil structure, low soil fertility, and poor soil biodiversity (Abawi and Widmer 2000). In such conditions, the incidence of potato fungal diseases such as scurf may increase, resulting in low yields and tubers with poor quality. The rotation of potatoes with cover crops and the addition of organic materials into soil may counteract these effects.

The use of cover crops, i.e. crops grown for the protection and enrichment of the soil, is a common practice for improving soil characteristics with potential benefits for crop productivity. The use of cover crops in rotation with potatoes has been shown to improve soil characteristics and suppress soil-borne potato diseases (Larkin et al. 2010; Larkin and Halloran 2015). Potato rotations with cover crops can help manage diseases by (i) serving as a break in the host–pathogen cycle; (ii) changing physical, chemical or biological soil properties, resulting in the stimulation of microbial activity and a diversity or an increase in beneficial soil organisms, which also can inhibit pathogens, and (iii) producing substances that supress pathogens and/or parasitic nematodes (Larkin et al. 2010). Since soil-borne diseases are affected by soil biology, organic soil amendments may also be applied to potentially reduce infections. Several types of organic residues, such as farmyard manure, and more recently digestate and biochar, can be used either directly or after suitable treatment as amendments to restore and improve soil characteristics. However, some organic materials may also serve as a host for pathogens, increasing the infection rate of soil-borne diseases.

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The use of cover crops and the addition of organic materials to improve soil characteristics are not new practices in agriculture. Yet, potato growers in Norway have been reluctant to use these practices as they do not see the immediate benefits for soil and crop productivity. Furthermore, the use of biochar and digestate as soil amendments is a completely new practice for Norwegian farmers. There is therefore limited information on the potentially beneficial effect of cover crops and organic soil amendments in potato production under Norwegian conditions. In the present study, we assessed the impact of a single application of three organic soil amendments on SOM and nutrient concentrations, potato yields and potato quality under field conditions with and without cover crops. The soil amendments were biochar + liquid digestate (B + LD), solid digestate (SD), and farmyard manure (FYM). We also performed a laboratory incubation to assess the carbon (C) storage potential of the organic materials. Our main hypotheses were that (i) a single addition of organic materials to soil and the presence of a cover crop will increase SOM and therefore improve soil conditions, leading to decreased incidence of potato diseases; (ii) because of differences in recalcitrance of C of the applied organic materials, SOM concentrations after two years will be highest in treatments receiving one application of B + LD, followed by SD and FYM; and (iii) soil respiration measured in the laboratory reflects the decomposition in SOM under field conditions over time.

Materials and methods

Site description

The study site was located in Grøa in Sunndal municipality, Møre og Romsdal county in Norway (6.6438°N, 8.7246°E), with an elevation of 45 m above sea level. This area has a temperate, humid climate (Figure 1) with an annual average precipitation of 998 mm and a mean annual temperature of 7.6°C. The experimental soil had an average $pH_{(H2O)}$ of 5.3 and a 2.47% loss on ignition, with a field bulk density of 1.55 g cm^{-3}. Ammonium-acetate lactate (AL)-extractable nutrients (Égner et al. 1960) are used to characterise soil fertility in Norway. The content of phosphorus (P) was assessed as very high (18 mg P-AL 100 g air-dry $soil^{-1}$), whereas the potassium (K) status was medium, 8.7 mg K-AL 100 g air-dry $soil^{-1}$ (Krogstad 1992).

Organic materials for soil amendment

Biochar was produced by Standard Bio AS in Bø, Telemark, Norway, by subjecting wood chips from Norwegian pine to pyrolysis at 400°C for 5 min (fast pyrolysis). Solid and liquid digestates were obtained from the biogas plant Ecopro AS in Verdal, Trøndelag, Norway. The digestate was derived from the digestion of mixtures of sewage sludge, source-separated organic household waste, organic waste from the food industry and fish sludge from freshwater aquaculture. The digestate is separated into a liquid and a solid phase at the biogas plant. Farmyard manure was horse manure mixed with sawdust, collected from a horse stable close to the experimental field. Chemical characteristics of the materials are presented under Results.

Field experiment

The field experiment was established on 10 July 2019, shortly after the harvest of early potatoes, on a field near the potato packaging company Sunndalspotet AS in Grøa, Sunndal, Norway. Experimental plots (3.3 m × 10 m = 33 m^2, with a total experimental area of 792 m^2) were established on a field with a history of silver and black scurf infestations. The experimental design was split plot with three replicates. The presence or absence of winter rye (*Secalis cereale* L.) as cover crop was the main factor (plot) and organic amendment types were the secondary factor (subplot). Ryegrass is often used as a cover crop, but winter rye was chosen because annual ryegrass would not survive the winter whereas perennial ryegrass could easily become a weed problem. Winter rye was grown as a cover crop (CC) between crops of potatoes in the autumn and winter of 2019–2020 and 2020–2021. Potatoes were the main crop on the experimental field in 2019 (year 0; tuber yields not recorded), 2020 (year 1) and 2021 (year 2), and the planting, fertilisation and crop protection of experimental plots were conducted by the farmer according to normal practice. The organic amendment treatments were: biochar + liquid digestate (B + LD), solid digestate (SD) and farmyard manure (FYM), compared with a Control (no OM). Biochar and liquid digestate were mixed on-site with a concrete driller two hours before their application. We aimed for application rates corresponding to 1.5 kg carbon (C) dry matter (DM) m^{-2}, to comply with a commonly used rate of biochar application of 15–30 Mg ha^{-1} (Ministry of Agriculture and Food, Ministry of Climate and Environment, Ministry of Health and Care Services. 2021) as well as the maximal amount of dry matter allowed for Class I organic fertilisers by Norwegian authorities (Ministry of Agriculture and Food et al. 2022). For our experiment, this amounts to 40 t DM ha^{-1} over 10 years (Rittl et al. 2022).

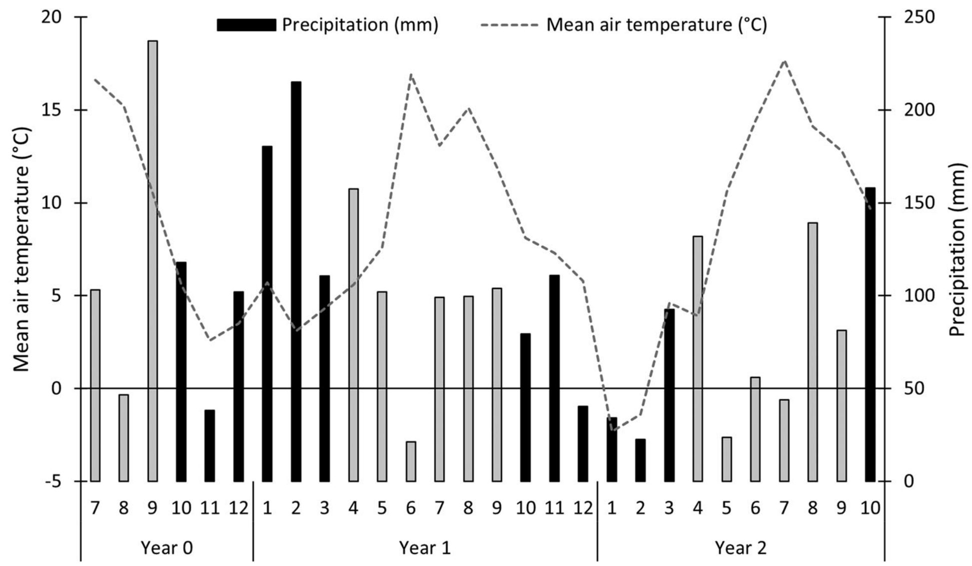


Figure 1. Monthly averages of air temperature (2 m above ground) and monthly accumulated precipitation during the field experiment, recorded on the nearby weather station Sunndalsøra III. Light grey columns show the precipitation during the growing season, from April to September.

Organic amendments were applied by hand to tilled soil on 10 July, year 0. On 11 July, plots were ploughed by tractor to a depth of 17 cm. Whereas the organic materials were applied only in year 0, CC was sown on half of the experimental field in year 0, year 1 and year 2 after the potato harvest (see Table 1 for dates). Winter rye (100 kg seed grains ha^{-1}) was applied as CC, using the cultivars Traktor in year 0, KWS Fabrizio in year 1 and Inspector in year 2. In year 0, winter rye started to emerge ten days after sowing, but did not compete well with the weeds already present in the field, and the CC performed below our expectations. In year 1 and year 2, the CC canopy was cut about 6 weeks after seeding, which enabled the CC to compete better with the weeds. The other half of the field experiment had no CC but had a significant canopy of weeds since no weed control was carried out there in the preceding season. Opposite to our expectations, the winter rye did not survive until the following spring in any winter season. Potato tubers, cv. Solist were planted in mid-April in year 1 and year 2. The distance between seed tubers was 25 cm and the distance between rows was on average 83 cm (every second row 75 and 90 cm, due to tractor tyre width). Each subplot comprised 4 rows of potatoes. The experimental plots were equally fertilised with a compound mineral fertiliser (YaraMila 12-4-18 micro) equivalent to 144 kg nitrogen (N) ha^{-1}, 48 kg P ha^{-1} and 216 kg K ha^{-1}, and 450 kg ha^{-1} of Polysulphate equivalent to 52.2 kg K ha^{-1}, 54.9 kg calcium (Ca) ha^{-1}, 16.2 kg magnesium (Mg) ha^{-1} and 86.4 kg sulphur (S) ha^{-1}, to cover the nutrient demand for a normal potato crop in this area. Fertiliser applications were the same across all treatments, so that nutrition would not limit crop growth in any treatment or the Control, and thus treatment effects would likely be related to factors other than fertility. Other details of the experimental management are presented in Table 1.

Sampling and analyses of organic amendments

Representative samples (3 l) of each organic amendment were collected on the day of application and stored at 4°C until being sent for chemical analysis at Eurofins, Germany for potentially toxic elements (PTEs; heavy metals), extractable macro and micronutrients and basic physiochemical characteristics. The standard set of analyses has been developed for composts by Eurofins, and includes analyses of dry matter content, bulk density, loss on, pH_{H2O}, total N (Kjeldahl), ammonium-N, nitrate-N, total organic C, AL-extractable nutrients, Olsen-extractable P, and total P. Total K, Ca, Mg and Na, micronutrients and potentially toxic elements As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn are presented in Rittl et al. (2022).

Soil sampling and analyses

In year 0 and year 2, between soil tillage after potato harvest and the sowing of CC, soil samples were taken from a depth of 0–20 cm (Table 1). Twelve soil cores were collected per plot and pooled for analysis of AL-extractable nutrients (P, K, Mg, Ca, and sodium (Na), loss on ignition, pH (soil: water 1:2.5 by volume) and bulk

Table 1. Dates and management operations performed in the field.

Date	(year, day, month)	Management operations
year 0	15-Jun	Harvest of early potatoes on the surrounding field, by farmer's equipment 09-Jul Soil tillage by tractor harrowing
	10-Jul	Soil sampling, field characterisation
	10-Jul	Application of soil organic amendments: biochar (133 kg/plot) + liquid digestate (265 L/plot); horse manure (352 kg/plot); solid digestate (476 kg/plot)
	11-Jul	Incorporation of soil organic amendments by ploughing to 17 cm soil depth
	23-Jul	Soil sampling for chemical analyses
	24-Jul	Planting seeds of winter rye 100 kg ha^{-1} by Nordsten Combi sowing machine, compaction by tractor and roller
	13-Aug	Re-seeding winter rye by using a hand seeding machine, compacting the soil by foot
	26-Sep	Sampling and visual assessment of the coverage of cover crop, average amount of the canopy cut to 5 cm stubble height inside of 50 cm x 50 cm frames randomly located on each experimental plot, n = 3
year 1		
	11-19-April	Planting of seed potatoes, application of fertilisers (one operation by commercial equipment). Tractor with Underhaug 3000 2-rows potato planter. Two and two rows were covered with plastic just after planting.
	12-Jun	Visual assessment of potato canopy vigour and sampling of petioles
	16-Jun	Harvest of early potatoes on the surrounding field, by farmer's equipment. Recording of potato yields in experimental plots
	26-Jun	Quality assessment of fresh potato tubers
	14-Jul	Soil tillage by tractor harrowing
	15-Jul	Winter rye sown 100 kg seed grains ha^{-1} by Øyjord Plot Seeder (Walking type), compaction by tractor and roller
	04-Sep	Weed control by cutting the canopy with a two-wheel walking mower.
	18-Oct	Sampling and visual assessment of winter rye canopy using a wood frame and scissors (see above)
Year 2		
	18-April	Planting of seed potatoes, application of fertilisers (one operation by commercial equipment). Tractor with Underhaug 3000 2-rows potato planter. Two and two rows were covered with plastic just after planting.
	11-Jun	Visual assessment of potato canopy vigour and sampling of petioles
	15-Jun	Harvest of early potatoes on the surrounding field, by farmer's equipment. Recording of potato yields in experimental plots
	21-Jun	Quality assessment of fresh potato tubers
	29-Jun	Soil tillage by tractor harrowing
	30-Jun	Soil sampling for chemical analyses
	30-Jun	Winter rye sown 100 kg seed grains ha^{-1} by Øyjord Plot Seeder (Walking type), compaction by tractor and roller
	23-Aug	Weed control by cutting the canopy with a two-wheel walking mower.
	18-Oct	Sampling and visual assessment of winter rye canopy using a wood frame and scissors (see above)
	28-Oct	Quality assessment of potato tubers after storage

density at Eurofins laboratory, Germany. Loss on ignition is closely related to the concentration of SOM and may be applied as a proxy for this parameter. Determination of AL-extractable nutrients followed the method developed by Égner et al. (1960), where the soil is extracted with 0.1 M ammonium lactate and 0.4 M acetic acid, pH 3.75 with a ratio of soil to solution of 1:20. Bulk density is measured by weighing a cylindrical container with a known volume, which is filled by shock exposure with sieved and air-dry material (soil or compost) and then re-weighed for bulk density calculation.

Cover crop sampling and nutrient composition analyses

The canopy of cover crops was cut with scissors to a stubble height of about 5 cm inside three randomly located wood frames sized 0.5 m × 0.5 m in autumn of year 0, year 1 and year 2 (Table 1), weighed in the field (fresh weight) and dried at 40°C until reaching a constant weight for determination of dry weight and total dry matter (DM, %). Because of the large proportion of weeds in the CC canopy, we determined the % of coverage of the winter rye in each plot by visual estimation on the sampling day. The proportion of CC coverage was used to calculate the dry weight of the winter rye fraction. Samples were sent to a commercial laboratory (ACTLABS, Activation Laboratories Ltd., Ancaster, Ont., Canada) for the determination of element concentrations (N, P, S, K, Mg, Ca, Na, Fe, B, Cu, Mn, Zn, Al) each year. Whereas this paper presents N, P and K concentrations, other elements are presented in Rittl et al. (2022).

Sampling and nutrient composition of potato petioles

In year 1 and year 2, potato petioles were collected for analyses of elemental composition to study to which extent the potatoes had covered their nutrient demand and especially the need for N, and if their nutritional status differed between treatments or between treatments and the Control. In each plot, the youngest fully expanded compound leaf was collected from 30 plants. The leaflets were separated from the petiole and discarded. The petioles were dried for 24 h at 50° C. Plant tissue concentrations of P, S, K, Mg, Ca, N, B, Mn, Zn, NO_3 were analysed using Yara Megalab, UK.

Tuber yield and quality assays

In June of year 1 and year 2, potatoes were manually harvested in harvest plots located on the two centre rows in each subplot, with a length of 4 m in year 1 and 6 m in year 2. The total weight of fresh tubers was recorded in field and corrected for the number of plants per harvest plot. Quality assays were performed in year 1 and year 2 within one week after harvest and in year 2 again after 4-month storage at about 12°C. For each quality assessment and per subplot, a subset of the harvested tubers amounting to 5 kg in year 1 and 10 kg in year 2 was graded and sized into 4 categories <40 mm, 40–50 mm, 50–60 mm, and >60 mm. The fresh weight of each category was recorded. Potatoes sized 40–50 mm were further assessed for their quality. In year 2, the 40–50 mm potatoes were divided in two, where one aliquot was used for the quality assessment of fresh tubers and the other was stored for later assessment. For the quality assessment, 40–50 mm potatoes were sorted into nine different categories, where eight were discarded due to various diseases or other defects, and the remaining category was marketable potatoes. When skin disease such as silver scurf (*Helminthosporium solani*), black scurf (*Rhizoctonia solani*) or skin spot covered > 10% of the potato surface, the potato was sorted out. Black scurf and silver scurf are soil-borne diseases of special importance in potato growing. Black scurf can negatively affect germination and growth of seed potatoes, especially in cold and wet seasons, and also negatively affect potato quality as potatoes may develop near the soil surface, increasing the proportion of greened tubers. Silver scurf does not cause any visible symptom on the potato canopy, but the fungus causes blemishes and silvery lesions on the potato tubers that develop during storage, dependent on humidity and temperature conditions. Potatoes were also sorted out due to growth and micro cracks, green skin, blemishing, hollow heart, mechanical damage, and deformation or other defects.

Incubation study

The incubation study had six organic material treatments comprising B + LD, FYM and SD × 2 application rates (low and high), and one Control (soil only). High-rate treatments (H) were equivalent to the application rates used in the field experiment, and low-rate treatments (L) were half of the rates used in the field experiment. For the experiment, 75 g of sieved (< 2 mm) and air-dried soil plus 0.75 or 1.5 g of B + LD, 2.35 or 4.7 g of FYM or 1.8 or 3.6 g of SD were filled in incubation jars (250 ml volume) and vigorously mixed. For the Control, 75 g soil was used. All treatments and the Control were replicated four times (n = 4). The moisture of the soil and soil-OM mixtures in the jars was adjusted to 60% of the maximal water holding capacity (Rittl et al. 2022) and maintained at that level throughout the experiment by weighing the jars and adding water if necessary. Samples were incubated at room temperature (about 20°C) for 727 days, except during three dates of controlled freeze and thawing on days 265, 288 and 330. On these dates, samples were frozen at −20°C for 48 h and then thawed in a water bath at about 40°C for 24 h. Freeze-thawing events are common in the region, and are known to impact the soil N and C cycles.

Soil respiration was measured using a wireless Pasco CO_2 sensor. The sensor has a one-point calibration in the software with a default value of 400 ppm. The wireless CO_2 sensor was operated through a tablet using the SPARKvue software. CO_2 measurements were performed over 3 min per jar and measuring date with one measurement of CO_2 every 15 s, resulting in 12 measurements of CO_2 per bottle per sampling date. Samplings were performed daily on day 1–5, then biweekly until day 132, and finally monthly until day 727. CO_2 concentrations were calculated and expressed per g of air-dried soil. Accumulated CO_2 emission was calculated by adding up daily CO_2 emissions over time.

At the end of the experiment (day 730), we measured the microbial carbon content (MBC) and proportions of fungi and bacteria using the microBIOMETER® test. For that, about 0.5 g of soil was dispersed with reagents, and the microbial carbon content (μg C g soil^{-1}) and the ratio of fungi and bacteria quantified by colour using microBIOMETER® app.

Calculations and statistical analyses

Analyses were performed in Minitab Statistical Software. We used variance analysis applying a general linear model (GLM) to compare the effect of organic amendments and cover crop on soil characteristics and nutrient concentrations in potato petioles. Organic amendment (No OM (Control), B + LD, SD, FYM) and cover crop (CC, no CC = NCC) were fixed factors, and year and/or subplot (for OM) were covariate factors. Effects of organic amendments on soil characteristics were analysed at establishment in year 0 and at the end of the study in year 2, while the effect of CC and the interaction between CC and organic amendment for soil characteristics were only measured in year 2. The effect of organic amendment on the CC yield was tested by one-way variance analysis (ANOVA) separately for year 1 and year 2, organic amendments or absent as a fixed factor.

Effects on potato yield and potato quality by organic amendments and CC were tested by variance analysis (GLM) separately for year 1 and year 2, with organic amendment and CC as fixed factors. When no significant interaction between organic amendment (OA) and CC

(CC × OA) was found, results were presented as main effects of OA or CC. Correlation analyses were conducted (using Pearson's correlation coefficients) among potato yield, proportion of marketable potatoes, soil characteristics, and potato petiole nutrient concentrations.

Differences between treatments, or between treatments and the Control, were considered statistically significant at $p < 0.05$. Significant differences were assigned by the Tukey t-test. Results with p-values between 0.05 and 0.08 are presented as trends.

The SOC stocks in the 0–20 cm soil layer were calculated as:

$$\begin{aligned}\text{SOC (Mg ha}^{-1}) =& (\text{Loss on Ignition (\%)} \\ & - \textit{correction for clay content}) \\ & \times 0.5(\text{conversion factor for SOM}) \\ & \times \text{bulk density (kg l}^{-1}) \\ & \times \text{soil depth (cm)}\end{aligned}$$

The correction for clay content takes into account the loss in weight during loss of ignition which is caused by loss of crystalline water content in clay minerals. Here, we used minus 2 as the correction which is commonly used in Norway for silt and fine sand soils (Riley 1996). The conversion factor from SOM to SOC is that proposed by Pribyl (2010).

For the incubation study, we used variance analysis (GLM) to compare the effect of organic amendments (type and rates) on the accumulated CO_2-C emissions. The relative contribution of each organic amendment was calculated by subtracting the emissions of the Control (only soil). The constant decomposition rate (-k) of organic C was estimated using the formula k = -(lnCf-lnCi)/ (tf-ti), where Cf is the remaining OM-C content (g C m^{-2}), Ci is the initial OM-C (g C m^{-2}) and tf-ti is the number of days since initiation of the experiment. Cf was estimated by subtracting the accumulated emitted CO_2-C from the initial OM-C content. Half-life (HL) and mean residence time (MRT) of the organic material applied in each amendment (in years) were estimated using the formula HL = ln(2)/k and MRT = HL/ln(2).

Table 2. Characteristics of the organic materials applied in the field experiment, $n = 1$. DM = dry matter.

Characteristics	Unit	B + LD	FYM	SD
Total Nitrogen (N)	% DM	2.52	1.42	3.67
NH_4-N	mg/kg DM	4800	27	5110
NO_3-N	mg/kg DM	2500	12.1	25000
Total Carbon	% DM	63.7	32.3	32.1
C/N	____	25	23	9
pH	____	7.7	7.6	8
Dry matter (DM)	%	14	32.6	27.5
Loss on ignition	%	96.7	79.4	62.7
Compact density	g/l	680	500	560
P-AL	mg/100 g air dried	6.7	110	45
P-Olsen	mg/100 g air dried	3.1	48.7	16.1
Total phosphorous (P)	mg/kg dm	1300	4500	22,000
K-AL	mg/100 g air dried	310	820	160
Mg-AL	mg/100 g air dried	23	99	77
Ca-AL	mg/100 g air dried	57	310	1200
Na-AL	mg/100 g air dried	160	260	110

B + LD = biochar + liquid digestate; FYM = farmyard manure; SD = solid digestate.

Results

Characteristics of organic amendments

The characteristics of organic amendments are shown in Table 2. The concentrations of total N, ammonium (NH_4-N) and nitrate (NO_3-N) were much higher for SD than for FYM. As expected, the total organic carbon (TOC) content of B + LD was higher than in FYM and SD. Due to the higher N content in the SD, the C/N ratio was lowest in this amendment. The pH of the three organic amendments was slightly alkaline, at pH 7.6–8. Loss on ignition of the organic materials applied in the soil ranged from 63% for SD to 97% for B + LD. Extractable phosphorus concentrations (P-AL and P-Olsen) were highest for FYM and lowest for B + LD. SD was rich in extractable Ca, whereas FYM had the highest concentration of extractable K, Mg and Na.

Winter rye yield and nutrient concentrations

In all seasons, the proportion of winter rye in the CC canopy was higher with the application of OM (Table 3). The addition of OM to the soil did not affect the dry weight of the CC canopy (winter rye plus weeds), but the estimated dry weight of only winter rye was higher in year 0 and year 2 in the SD treatment (Table 3). The uptake of N in the CC canopy (rye + weeds) varied significantly between treatments in year 0, with the highest uptake from SD, but not in subsequent years (Table 3). In year 1, all treatments had higher yields of winter rye than the Control, but the CC yields were generally low that year. In year 2, the cover crop still responded to the addition of organic amendments in year 0, with the SD producing more biomass than the other treatments (Table 3).

Soil pH, extractable nutrients and SOM concentration

After one application of organic materials in year 0, and two seasons of growing a cover crop, we found significant effects of organic amendments and CC on some soil characteristics in year 2, but no significant interaction between OM and CC for pH, SOM or AL-extractable nutrients (P, K, Ca, Mg, Na) (Supplementary Material, Table 1). Hence, results are presented as main effects of organic amendments and CC (Table 4).

The organic amendments significantly affected soil pH, SOM concentrations (loss on ignition) and extractable Ca. Soil pH increased significantly with SD, and this treatment also increased the Ca-AL concentration. Significant increases in SOM were found for FYM and B + LD. The SOC stocks (Table 4) showed the same trends as the SOM concentrations (Figure 2). In year 2, SOM concentrations were lower than in year 0 for all treatments. Yet, in year 2 the SOM concentration in the treatments with the application of organic materials was 4%, 7% and 8% higher for SD, B + LD and FYM, respectively, as compared with the Control; for the two latter amendments the difference was statistically significant. Hence, the general reduction in OM in this intensively managed soil over time seems to be counteracted by the application of organic materials, whereas for CC the increase was not significant.

Potato petioles

Potato petioles were collected for analyses of elemental composition to study to which extent the potatoes had covered their nutrient demand and especially the need for N, and if their nutritional status was affected by OM application. The major mineral nutrient in potato petioles, comprising 8–8.5% of the DM, was potassium (Table 5). The concentrations of P and S were similar, and somewhat above the concentrations of Ca and Mg. For concentrations of the micronutrients manganese (Mn), zink and boron, Mn comprised the largest concentration (Table 5). The concentration of NO_3 was low (< 20 ppm), which shows that the fertilisation was not excessive.

There was no significant interaction between OA and CC on the concentrations of various elements or NO_3 in the potato petioles, except for manganese (Mn) ($p =$ 0.018). Overall, the element concentrations were significantly higher in year 1 than in year 2 (Table 5).

Organic amendments significantly affected on the concentrations of Ca, S, P, K and Mn, while the presence of CC affected the concentrations of Mn, Zn and B. Overall, the accumulated concentration of K + Ca + Mg + S + P (% of DM) and NO_3 was lowest in the petioles in the treatment with the addition of SD and the presence of CC, and highest with FYM without CC. These differences were mainly due to the K level, which varied considerably between the treatments. For the accumulated concentration of Mn + Zn + B + NO_3 (ppm), the Control showed the highest value, mainly due to a higher concentration of Mn in the potato leaves compared to the treatments.

Tuber yield and marketable potatoes

There was no significant interaction between the application of organic amendments and cover crop on the total tuber yields (hereafter tuber yields), or on the proportion of marketable potatoes (40–50 mm, with no visual defects or skin disease). Hence, results are presented as the main effects of organic materials (OM) and CC (Figure 3). In year 1, tuber and marketable potato yields were not significantly affected by the addition of OM or the presence of CC. The highest tuber yields were recorded in the treatments with CC and FYM, and the lowest in those with SD. On average, the potato yield with CC was 16.4 tons of tubers per hectare. Differences between OM treatments were small, with FYM giving the highest yield of 16.6 tons of tubers per hectare, and SD

Table 3. Cover crop % of coverage, total dry weight (CC + weeds) and estimated cover crop dry weight, total NPK uptake in treatments receiving a single application of various organic materials in year 0. Within each year and characteristics, different letters indicate statistically significant differences between treatments, Tukey test ($p < 0.05$).

Year	Treatment	CC %	Total dry weight (CC + weeds) kg DM ha^{-1}	Cover crop dry weight	Total uptake kg ha^{-1} N	K	*P*
0	No OM	21	1128 a	235 b	35 ab	39 a	8 a
	B + LD	35	1191 a	417 ab	43 ab	53 a	8 a
	FYM	34	926 a	316 ab	26 b	32 a	6 a
	SD	43	1235 a	535 a	54 a	52 a	8 a
1	No OM	25	398 a	100 b	16 a	15 a	3 a
	B + LD	37	453 a	166 a	20 a	18 a	3 a
	FYM	42	439 a	183 a	18 a	17 a	3 a
	SD	37	501 a	184 a	22 a	20 a	3 a
2	No OM	17	1180 a	197 b	38 a	44 a	8 a
	B + LD	33	1080 a	360 ab	36 a	43 a	7 a
	FYM	27	1127 a	300 b	36 a	46 a	8 a
	SD	50	1413 a	707 a	42 a	54 a	10 a

B + LD = biochar + liquid digestate; FYM = farmyard manure; SD = solid digestate.

Table 4. Mean values (year 2) for soil pH, AL-extractable nutrients (mg/ 100 g air-dry soil) and SOC stocks (Mg ha^{-1}). For each characteristic, different letters (a, b) indicate statistically significant differences between organic amendments and the Control, or between treatments with and without cover crop (CC). Tukey test ($P < 0.05$).

Characteristics	Control	Biochar + LD	Farmyard manure	Solid digestate	NCC	CC
pH	5.01b	5.05b	5.13ab	5.28a	5.08a	5.15a
P-AL	19.2a	21.5a	19.0a	20.2a	21.5a	18.4b
K-AL	9.0a	9.7a	10.3a	9.0a	9.7a	9.3a
Mg-AL	5.3a	5.7a	7.0a	5.7a	5.8a	6.0a
Ca-AL	36.7b	37.2b	40.0ab	44.3a	38.4a	40.7a
Na-AL	3.0a	3.0a	4.7a	3.7a	2.8b	4.3a
SOC stocks	30b	32ab	32a	31ab	31a	32a

LD = liquid digestate; NCC = no cover crop; CC = cover crop.

the lowest with 15.5 tons of tubers per hectare. The Control yield was not significantly different from OM treatment yields in any year. The overall tuber yield was comparable in year 1 and year 2, 16.04 vs. 16.18 Mg ha^{-1}. In year 2, the tuber yield was significantly higher with FYM than with SD applied in year 0, and there was a significant increase in tuber yield with CC. The differences were not statistically significant for the marketable yields at potato harvest. In both years, the marketable yield at harvest was about 85% of the total tuber yield.

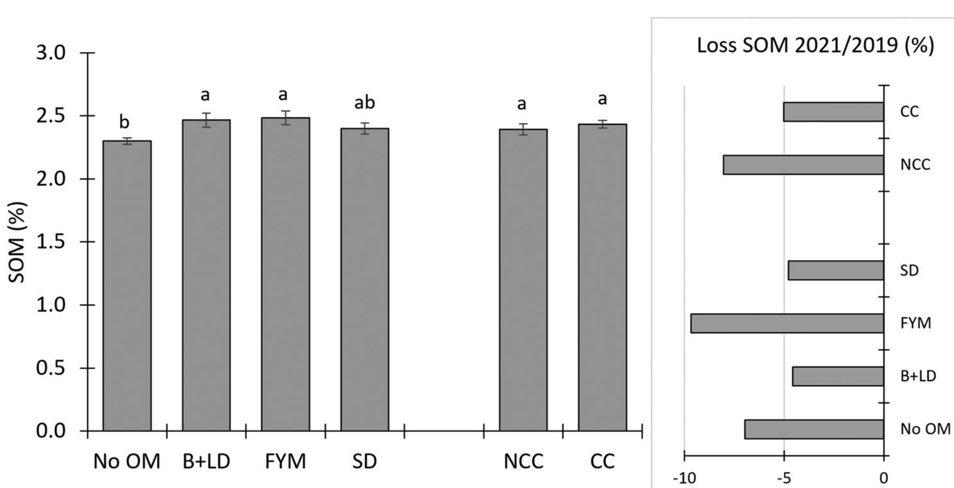
After 4 months of storage in year 2, the marketable yield had decreased significantly in all treatments (Figure 3). CC had a positive effect on potato quality during storage, since the average marketable yield was 11.5 Mg ha^{-1} with CC, and 8.3 Mg ha^{-1} without CC.

In the three quality assays, tubers with green skin and blemished skin were not identified. Deformed potatoes and potatoes with other defects were the main problems identified in year 1. While in year 2 the main problems were scurf, micro cracks, and deformed potatoes (Figure 4).

Tuber yields and the proportion of marketable potatoes were significantly and positively correlated ($p <$ 0.001) with SOM and soil pH, and with the concentration of Mg, B, Zn, P, and NO_3 in the potato petioles, and significantly but negatively correlated with Mn and K concentrations in the potato petioles (Supplementary Material, Table 2).

Incubation study

Soil CO_2-C fluxes, an indicator of microbial activity, decreased over time in all treatments (Figure 5). Soils with organic amendment had higher CO_2 fluxes in the first weeks than the control soil, but this effect diminished with time. Accumulated CO_2 fluxes for the first 100 days of incubation varied from 19% of the total CO_2-C emitted from the low-rate B + LD treatment to 54% of the total CO_2-C emitted from the high-rate SD treatment. At the end of the first year, accumulated CO_2 fluxes varied from 57% of the total CO_2-C emitted from the low-rate B + LD treatment to 78% of the total



No OM= no organic matter; B+LD= biochar+liquid digestate; FYM= farmyard manure; SD=solid digestate

Figure 2. Mean values (year 2) of soil organic matter concentrations in treatments that received a single application of organic materials in year 0, and in plots with and without cover crops. Different letters indicate statistically significant differences ($n = 6$) between organic amendments, or for the effect of cover crop (CC). Loss on soil organic matter (%) in the treatments in year 2 compared to year 0.

Table 5. Mean values and *p*-values of nutrient concentrations in the potato petioles in treatments that received a single application of organic amendments in year 0, with winter cover crop (CC) and without winter cover crop (NCC).

Year, treatments	P	K	Mg	S	Ca	NO_3	Zn	Mn	B
	------%------					------ppm------			
Year 1									
Year 1 average	0.53	8.07	0.22	0.35	0.24	19	45	106	21
NCC average	0.53	8.21	0.20	0.35	0.25	20	48	115	22
No OM	0.53	8.13	0.20	0.39	0.21	20	50	131	22
Biochar + L	0.55	8.57	0.20	0.35	0.20	19	49	115	23
Horse Manure	0.54	8.19	0.20	0.33	0.20	20	50	107	22
Solid Digestate	0.50	7.97	0.20	0.33	0.38	19	44	107	21
CC average	0.52	7.93	0.24	0.35	0.24	18	42	96	20
No OM	0.52	7.84	0.27	0.34	0.21	18	42	100	21
Biochar + L	0.53	7.96	0.23	0.38	0.22	17	43	109	21
Horse Manure	0.53	8.35	0.20	0.35	0.20	18	43	87	20
Solid Digestate	0.51	7.55	0.27	0.34	0.32	20	40	89	20
Year 2									
Year 2 average	0.45	8.62	0.14	0.37	0.23	12	33	139	19
NCC average	0.45	8.70	0.14	0.38	0.23	12	35	146	20
No OM	0.46	8.41	0.17	0.43	0.21	11	38	194	20
Biochar + L	0.46	8.81	0.13	0.37	0.21	12	35	134	20
Horse Manure	0.47	9.11	0.17	0.38	0.19	12	33	128	19
Solid Digestate	0.39	8.48	0.10	0.34	0.31	12	34	127	20
CC average	0.45	8.53	0.13	0.36	0.23	13	32	132	19
No OM	0.45	8.79	0.17	0.36	0.20	14	33	127	19
Biochar + L	0.47	8.26	0.13	0.40	0.21	12	32	148	19
Horse Manure	0.49	8.48	0.13	0.36	0.19	12	31	129	19
Solid Digestate	0.39	8.58	0.10	0.32	0.31	13	31	123	19
P-value									
Year	**0.000**	**0.000**	**0.000**	0.151	0.196	**0.000**	**0.000**	**0.000**	**0.000**
CC	0.911	0.052	0.210	0.329	0.303	0.997	**0.000**	**0.008**	**0.004**
OM	**0.002**	**0.000**	0.316	**0.032**	**0.000**	0.585	0.061	**0.006**	0.460
CC *vs* OM	0.902	0.126	0.495	0.067	0.404	0.544	0.578	**0.018**	0.782

No OM = no organic amendment (Control); LD = liquid digestate; NCC = no cover crop; CC = cover crop

CO_2-C emitted from the high-rate SD treatment. In our study, C loss as CO_2 (CO_2-C) originating from OM ranged from 6 to 27% of the total C added with B + LD, 21–25% for FYM and 47–49% for the SD.

After two years of incubation, the microbial C content (MBC) varied from 9 to 90% in treatments with OM compared with the Control, but the differences were not statistically significant (Table 6). Across all treatments, low-rate FYM had the highest concentration of MBC (1292 µg C g soil^{-1}) and the high-rate FYM had the lowest (741 µg C g soil^{-1}). B + LD treatments had on average 958 µg C g soil^{-1} and SD treatments 1091 µg C g soil^{-1}. The ratio between fungi and bacteria (F:B) ranged from 1.5 for high-rate FYM to 2.8 for low-rate FYM, while in the Control the ratio was 1.3.

The constant decomposition rates (-k) ranged from 0.031 for the low-rate B + LD to 0.334 for the high-rate SD (Table 6), resulting in mean residential times of 3 years for SD, 7–8 years for FYM, and 6–32 years for the low and high-rates of B + LD. The decomposition rates (-k) and mean residential time values are estimates which should not be extrapolated to field conditions, where plants, climatic conditions and soil structure may play a major role in the stability of these materials.

Discussion

Effects of organic amendments and cover crop on SOM

As we expected, one single application of OM increased the concentration of SOM two years after the application (Figure 2), relative to the Control. Contrary to our expectations, the use of CC for three years had a negligible effect on SOM. The incubation study revealed that a large proportion of the OM was biologically available and could be degraded by soil microorganisms, especially for SD. The decrease of CO_2 fluxes after 20 days for B + LD and FYM is likely explained by a quick initial decomposition of the labile compounds of these materials. The FYM was relatively fresh, as indicated by the high concentrations of K, an easily leachable nutrient. Contrary to this pattern, SD seems to have a large pool of labile compounds, leading to continuous small CO_2 fluxes. It was somewhat surprising that biochar enriched with liquid digestate (B + LD) did not increase SOM to a greater extent than FYM and SD, as we expected initially. The wood-derived biochar used in the B + LD treatment was expected to have a high potential for soil C storage due to its intrinsic

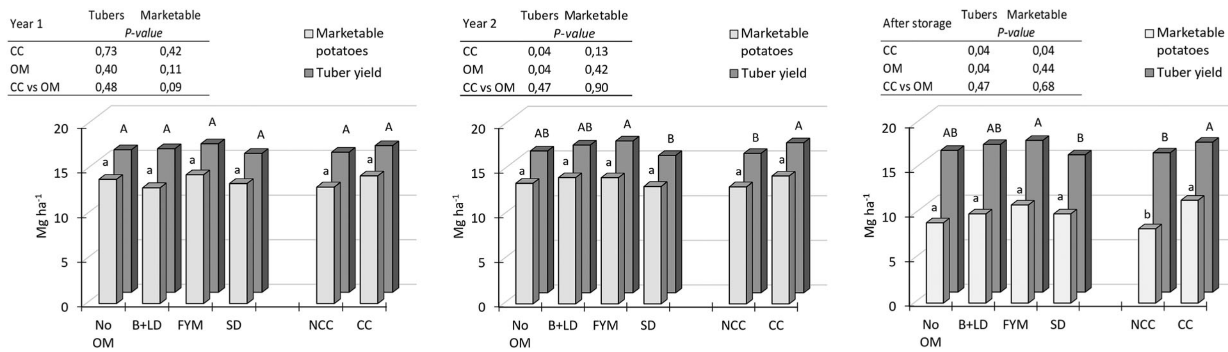


Figure 3. Tuber yield (Mg ha^{-1}, dark grey columns) and marketable yields (Mg ha^{-1}, in light grey) for the treatments with the addition of different organic materials (OM) and the control (No OM) and across treatments with (CC) or without cover crop (NCC) in year 1 (a), year 2 (b), and after 4 months of storage in year 2 (c). Inserted tables are the *p*-values for the effect of OM and CC and their interactions (CC × OM) on tuber and marketable yields.

biochemical recalcitrance (Schellekens et al. 2018). It is possible that the mixture of wood biochar with liquid digestate may have increased the decomposition of biochar, by lowering its C:N ratio (Table 2). Also, the freeze–thaw events had a higher impact on the decomposition of the organic compounds in the B + LD treatment than in the FYM and SD treatments (Figure 5). Chemically recalcitrant OM, such as biochar, is known to be more temperature-sensitive than more labile OM (Knorr et al. 2005; Nguyen et al. 2010). Despite their different chemical qualities, these materials decomposed similarly in the field and laboratory studies (Figures 2 and 5). The only exception was the low-rate B + LD treatment, which had the lowest decomposition rate and therefore the highest estimated mean residence time, 32 years. This might be due to the smaller proportion of labile C present in this treatment, which was likely the main source for the CO_2 emissions in the sandy soil with initially low C content.

Our results suggest (Table 6) that adding organic amendments may increase SOM in the sandy soil, but that this effect will be temporary, even for biochar with a high proportion of recalcitrant material. SOM persistence is an ecosystem property (Schmidt et al. 2011). OM applied to the soil will persist or degrade in the soil not only because of its intrinsic properties, but because of physicochemical and biological processes that affect the probability of decomposition (Schmidt et al. 2011). Our experimental soil was mainly composed of sand, where OM is mostly found as particulate organic matter and not protected by an association with mineral particles, as can be the case in more finely textured soils. Indeed, SOM accumulation in the B + LD and FYM treatments seems to have occurred more in the particulate fraction than in the mineral-associated fraction of SOM; data presented by Rittl et al. (2022). Because particulate organic matter is less protected, environmental changes that support microbial activity (e.g. thawing, draining) or disrupt aggregates (e.g. tillage) can immediately increase decomposition rate of particulate organic matter (Lavallee et al. 2019), resulting in a low potential for long-term C storage.

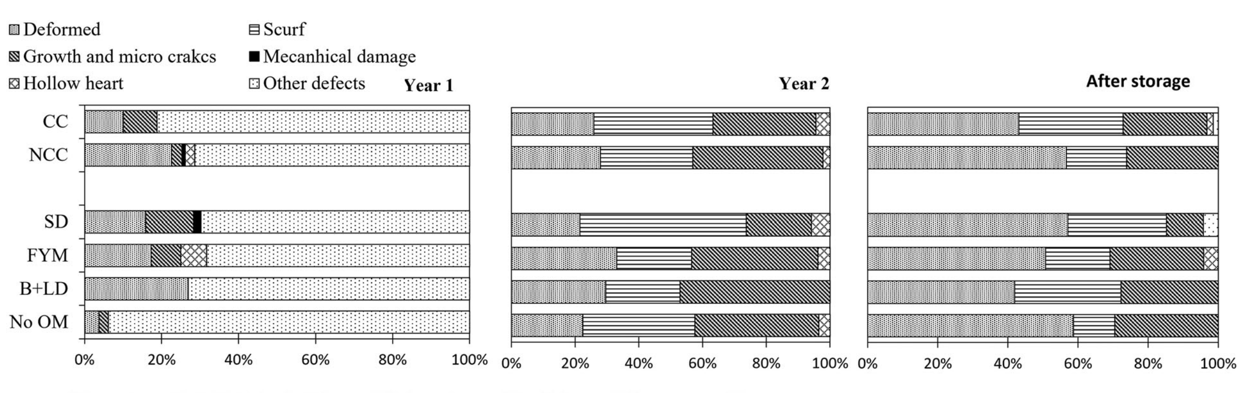


Figure 4. Sorted out tubers (%) in treatments with the addition of different organic materials (OM) and the control (No OM), and across treatments with (CC) and without cover crop (NCC) by harvest in year 1, year 2, and after 4 months of storage in year 2.

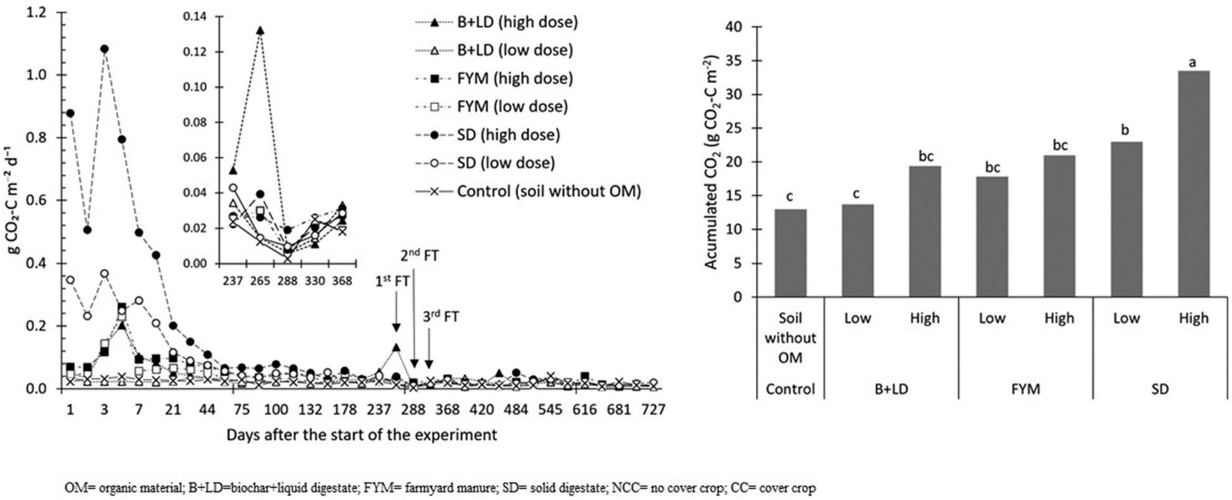


Figure 5. Daily CO_2 fluxes as g CO_2-C m^{-2} d^{-1} and accumulated emissions as g CO_2-C m^{-2} from sandy soil with organic amendments and effect of freeze–thaw events (FT). Mean values of 4 replicates per treatment.

Effects of OM and CC on soil fertility and nutrient availability

With CC, the concentration of AL-extractable P in the soil decreased significantly (Table 4), whereas extractable sodium (Na-AL) increased. The decrease in P-AL may indicate that P was taken up by the CC and lost during winter, since P in above-ground plant material is prone to get lost by leaching, especially with the unstable winter conditions that are common in Sunndal. In the winter of year 0, there was high precipitation during a mild winter in Sunndal, and in spring year 2 there was high precipitation in March and April just after a period of temperatures below 0°C (Figure 1). Since the CC did not survive the winter, and soil sampling occurred in June, the increase in Na-AL with CC is difficult to explain, but if the amounts of canopy were higher on CC plots in spring, this may have increased the soil concentration of Na-AL. CC did not affect soil pH or SOM (Table 4).

Table 6. Microbial carbon (MBC), fungi to bacteria ratio (F:B), decomposition rate ($-k$), and mean resident time (MRT in years) of the sandy soil amened different types and rates of organic materials incubated for 727 days.

OM	Applied rate	MBC (μg C g soil^{-1})	F:B ratio	($-k$)	MRT years
B + LD	High	988 ± 419	2.1	0.155	6
	Low	928 ± 164	2.0	0.031	32
FYM	High	742 ± 165	1.5	0.118	8
	Low	1292 ± 213	2.8	0.147	7
SD	High	1140 ± 547	2.5	0.334	3
	Low	1040 ± 180	2.2	0.321	3
No OM	Control	679 ± 131	1.3	-	-

B + LD = biochar + liquid digestate; FYM = farmyard manure; SD = solid digestate; OM = organic materials.

The decomposition of the organic amendments released nutrients, which probably increased the concentration of plant-available nutrients in the soil. Except for calcium, the concentrations of extractable soil nutrients were not significantly affected by OM application after two years (Table 4), but the concentrations of macronutrients in potato petioles were higher with FYM and B + LD, whereas for SD the concentrations were mostly significantly lower than in the Control (Table 5). Although, total P was very high for SD, reaching 22 g kg DM^{-1}, only a minor part of this was extractable (Table 2). This is likely because of the chemicals (Fe, Al) used to precipitate phosphorus from sewage. For nutrient concentrations in the potato petioles, no effect was found of organic amendment or CC, which indicates that neither the organic materials nor CC had a negative effect on the nutrient supply of the crop.

The tissue concentrations for the major nutrient elements (NO_3, P, K) for all treatments in our field study were within the normal (sufficient level) ranges (Agyarko et al. 2006), expect for Ca and Mg, which were below the sufficient level ranges (Table 5). This indicates a too low soil pH and a too high K-fertilisation, which may have resulted in a low uptake of Mg and Ca by the plants. Suboptimal concentrations of these nutrients may cause reduced tuber size and number, and increase the incidence of potato diseases (El-Hadidi et al. 2017). In our experiment, the concentration of Mg seems to have had a positive effect on both potato yield and the yield of marketable potatoes. A higher concentration of Mg in the petioles was related to an increase in tuber yield and the yield of marketable potatoes. However, we did not observe any significant relationship between the low concentration of Ca and a lower total tuber or the yield of marketable yield.

Effects of OM and CC on tuber yield and marketable potatoes

Contrary to an earlier study with ryegrass as a cover crop in Sweden (Bång and Wallenhammar 2008), we did not observe a negative effect of cover cop on marketable potatoes in any of the two growing seasons. Bång and Wallenhammar (2008) reported an increase in the infection rate of potatoes after rotation with ryegrass (Lolium) as a cover crop in their first trial (2007–2009). In the subsequent Swedish trial (2011), however, the negative results were not confirmed; on the contrary, the proportion of tubers affected by black scurf was significantly lower with Westerwold or annual ryegrass as cover crop than when Brassica species or oats (*Avena sativa* L.) were used as cover crops (Bång and Wallenhammar 2008). In our study, winter rye as a cover crop, sown after potato harvest, was shown to increase the total tuber yields as well as the proportion of marketable potatoes in both years (Figure 3). Although results vary from trial to trial and year to year, the use of cover crops has been shown to increase the potato yields between 6% and 12% and decrease the severity of soil-borne diseases (i.e. black scurf (*Rhizoctonia solani*) and silver scurf (*Helminthosporium solani*)) in trials where those diseases occurred (Larkin et al. 2010; Larkin and Halloran 2015).

The addition of FYM and B + LD also increased tuber yields compared to the control. These increases were presumably due to the beneficial effects of the CC and added OM in raising the content of SOM and nutrients, leading to an overall improvement in soil conditions and potentially reducing the severity of pathogens and soil-borne diseases. The addition of OM increased the content of microbial carbon in soil under laboratory conditions (Table 6). This indicates that the OM addition in the field may have led to changes in the soil's microbial community (Table 6), which may have supported the growth of beneficial soil microorganisms, thus suppressing soil-borne pathogens and decreasing potato diseases, especially in year 2. Yet, there was no clear impact of CC or organic amendments on specific potato diseases. Furthermore, the incidence of scurf was lower than expected, since the soil at the experimental site was infected with this disease. This may be because the soil conditions (temperature and moisture) were not ideal for fungi development in the growing seasons of year 1 and year 2.

Previous studies have indicated similar responses to organic amendments and cover crops in a number of different potato varieties, and improvements in soil conditions have been associated with increases in yield and quality across different production systems (Larkin et al. 2010, 2017, 2021). CC can suppress pathogens and potato diseases by modifying the soil microbial community and increase beneficial organisms (including biocontrol agents) in the soil (Benítez et al. 2007), while specific biofumigant CCs (brassica) can release metabolites which directly suppress soil-borne plant pathogens (Larkin et al. 2010, 2017, 2021); and also by altering the soil physical, chemical, or biological characteristics to stimulate microbial activity and diversity (Larkin et al. 2010, 2021). A rotation of potatoes with CC resulted in a lower incidence and severity of multiple soil-borne diseases (including stem canker, black scurf, and common scab) (Larkin et al. 2010, 2017; Larkin and Halloran 2015). Although our study was conducted using only one potato variety, Solist, our results may have implications for other potato varieties, including varieties commonly applied for storage, as we observed larger proportions of marketable potatoes after storage in the treatments with CC.

Final considerations

The use of cover crop is not a new practice in agriculture, but this practice is not common in Norwegian potato production. There is a lack of information about the best practices, benefits, and drawbacks of using cover crops in potato production under Nordic conditions. Here, we have shown that the use of winter rye as a cover crop after the harvest of an early potato crop increased total tuber yield and reduced the severity of potato diseases by 10% in post-harvest potatoes in both growing seasons of the experiment. Winter rye as cover crop has the potential to increase the percentage of marketable potatoes significantly after storage; we found an increased marketable yield after storage of 37%. We could not link this increase to a reduction of a specific potato disease, but our results confirm earlier reports on the benefits of using cover crops to cope with soil-borne pathogens. More research should be carried out to identify the mechanisms involved in disease suppression by cover crops.

Digestate and biochar are new materials for Norwegian farmers. Their use is expected to increase in the future due to increasing prices of fertilisers. Farmyard manure is well known to improve soil characteristics. The present study showed that the application of different organic materials could indeed increase soil OM, but organic materials were rapidly degraded with intensive soil management and continuous potato cropping. Farmyard manure (FYM) and biochar with liquid digestate (B + LD) had a higher potential for storage of soil OM than solid digestate (SD). B + LD had the largest potential for long-term soil organic matter storage, up to 32 years, followed by FYM and SD. The co-application of biochar with liquid digestate has the potential to become a climate-smart fertiliser, by combining the long-lasting C fraction of the biochar with the nutrients from the liquid digestate. The reduction in OM in this intensively managed soil over time seems to be counteracted by the application of organic materials, whereas for CC the increase was not significant.

The effect on soil-borne disease in potatoes is not well known, for any of the applied materials. We have shown in the present study that the addition of organic amendments did not affect tuber yield or quality, but the proportion of marketable potatoes tended to be higher in the treatments where organic amendments were applied, especially for FYM.

All in all, the results indicate that cover crops and organic amendments should be recommended for application in potato production, especially in early potatoes, where there is sufficient time after harvest to establish a good cover crop.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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