Effect of soil organic matter management on soil characteristics, potato yield and potato disease in an intensive potato growing system (MERMOLD)

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TITLE

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SUMMARY:

The MERMOLD project (2019-2022) was a collaboration between industry and research partners. The project was owned by Sunndalspotet AS and managed by the Norwegian Centre for Organic Agriculture (NORSØK). The other partners were Standard Bio AS, Ecopro AS and Landbruk Nordvest. Production of potatoes is a specialised industry, and commonly occurs on farms without animal husbandry. Hence, cereals are often the only other crop being grown, and with a lack of animal manure and growing of perennial ley, in combination with intensive soil tillage for potatoes, soil organic matter (SOM) tends to decline. The main objective of this project was to assess if cover crop and organic amendment practices could increase SOM storage, and possibly affect potato yields and soil-borne diseases. To do so, we established a field experiment in July 2019 to: (i) assess under field conditions with and without cover crop the impact of a single application of various organic materials to soil (biochar+liquid digestate, solid digestate, or farmyard manure) on SOM storage; (ii) quantify the impact of cover crop and application of organic materials on potato yields and potato diseases; (iii) discuss a suitable cover crop and organic soil amendment practice for potato cropping systems in this part of Norway. Furthermore, we performed a laboratory incubation to (iv) measure under controlled conditions the effect of organic amendments on carbon dioxide (CO_2) emissions from the experimental soil.

Our results show that: a single addition of organic materials increased SOM storage, especially in the farmyard manure and biochar+ liquid digestate treatments, while the presence of cover crop did not significantly affect SOM storage. Yet, the cover crop significantly increased potato yield in 2021 and reduced the severity of potato diseases by 10% in the post-harvest potatoes in 2020 and 2021, while the number of marketable potatoes after storage in 2021 was increased by 37%. Organic amendments did not significantly affect potato yield or quality, but the proportion of marketable potatoes tended to be higher in the treatments where organic materials were applied 2 years after the application.

SAMMENDRAG

MERMOLD prosjektet (2019-2022) var et samarbeid mellom industripartnere og FoU-aktører. Prosjekteier var Sunndalspotet AS, mens NORSØK hadde ansvaret for gjennomføringen av prosjektet. Andre partnere var Standard Bio AS, Ecopro AS og Landbruk Nordvest. Potetdyrking er en spesialisert produksjon, og som regel foregår den på gårder uten husdyrhold. Den eneste veksten utenom poteter er da gjerne korn, og med mangel på husdyrgjødsel og lite eng i vekstskiftet, kombinert med intensiv jordarbeiding i potetdyrkinga, vil dette ofte tære på moldinnholdet i jorda. Målet med MERMOLD-prosjektet var å undersøke om bruk av fangvekst, og tilførsel av organisk materiale til jorda kunne øke innholdet av organisk karbon (C) og om slike tiltak kunne påvirke potetavlingene og angrep på knollene av jordoverførte sjukdommer. Et feltforsøk ble etablert hos Per Grødahl på Gjøra i juli 2019 for å undersøke: (i) effekten på jordas moldinnhold av en enkelt tilførsel av ulike typer organisk materiale (biokull fuktet med flytende råtnerest; fast råtnerest; hestegjødsel) etter opptak av tidligpoteter, med og uten fangvekst, (ii) effekten av fangvekst (høstrug) og tilførsel av organisk materiale på potetavlinger og sjukdommer på knollene. Videre (iii) ble det diskutert hvordan fangvekst og tilførsel av organisk materiale kan gjennomføres i praksis i potetdyrkinga i Nordmøre og Sør-Trøndelag. Vi gjennomførte også et inkubasjonsforsøk med jord fra forsøksfeltet for å måle (iv) effekten av ulike typer og mengder av organisk materiale på utslipp av karbondioksid (CO_2).

Vi fant at en enkelt tilførsel av organisk materiale økte moldinnholdet, særlig ved tilførsel av hestegjødsel og biokull fuktet med flytende råtnerest. Bruk av fangvekst hadde ikke noen sikker effekt på moldinnholdet. Fangvekst økte imidlertid potetavlinga i 2021, og ga 10% reduksjon i sjukdomsangrep i poteter etter lagring i både 2020 og 2021. Andelen av salgbare poteter etter lagring økte med hele 37% i 2021 ved bruk av fangvekst. Det var ikke noen sikker effekt av tilførsel av organisk materiale på avling eller kvalitet av poteter, men tendensen var at andelen av salgbare poteter i 2021 var høyere i behandlinger som fikk tilført organisk materiale i 2019.

COUNTRY:	Norway
COUNTY:	Møre og Romsdal
MUNICIPALITY:	Sunndal
LOKALITET:	Gjøra

APPROVED	**PROJECT LEADER**
Turid Strøm	Tatiana F. Rittl
NAVN	**NAVN**

Preface

MERMOLD was a three-year project funded by RFF Møre og Romsdal, where the application of organic materials and use of cover crop were tested to see if this could improve soil conditions and potato quality. Such improvements may increase the profit for potato farmers. The methods tested here have the potential to be applied in both organic and conventional potato growing.

Participating industry partners in the MERMOLD project were Sunndalspotet AS (project owner), Ecopro biogas plant (Verdal, Trøndelag) and StandardBio AS (Bø, Telemark). Ecopro delivered solid and liquid digestate for the MERMOLD field experiment. Ecopro is one of the oldest biogas plants in Norway, with a long record of active involvement in research and development activities, including efficient utilization of the digestate as fertilizer and soil amendment. StandardBio delivered biochar produced from pine wood. Landbruk Nordvest and NORSØK collaborated to conduct field experiments, and significant assistance was provided by the local farmer, Per Grødal, who is kindly acknowledged.

On behalf of NORSØK, we want to thank all partners involved in the MERMOLD project, and the financial and professional support from RFF Møre og Romsdal.

Tingvoll 30.06.2022

Anne-Kristin Løes and Tatiana Rittl (project leader)

Frontpage photo: Field experiment in 2019, shortly after the application of organic materials. Photo: Tatiana Rittl

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1 Introduction

Over the past 40 years, potato growth in Nordmøre has been in a crop rotation system with mainly potatoes and cereals and without the presence of livestock. Instead, local farmers have developed a successful and quite intensive potato cultivation, with a local packaging plant (Sunndalspotet) taking care of storage, washing, sorting, packaging, and distribution locally. The absence of livestock manure and crop rotations with ley has led to a rapid decline of soil organic matter (SOM) content, also because the local soil type, sandy soil does not protect the SOM as well as in more finely textured soils. This decline may lead to potential loss of productivity, increase of soil erosion and increasing problems with soilborne fungal diseases such as black scurf (*Rhizoctonia solani*) and silver scurf (*Helminthosporium solani*). Black scurf can affect negatively on germination and growth of seed potatoes, especially in cold and wet seasons, and affect negatively on potato quality as potatoes may develop in the soil surface, increasing the proportion of greened tubers. Silver scurf can produce a surface blemish on the potatoes, causing red varieties to look “dirty”, especially towards the end of the storage period. Both diseases occur in Sunndal and are a challenge for the potato growers.

This situation made Sunndal an ideal case to study measures to increase SOM, which is also a highly relevant topic for Norwegian agriculture in general with respect to climate mitigation. Among the agricultural practices used to increase SOM content in agricultural soil, cover crops and addition of organic amendments into soil are the most effective. Although these practices have been applied in potato crop systems elsewhere (Larkin, et al., 2010; Lazarovits et al. 2007), they have not yet been implemented in potato cropping systems in Nordmøre. Addition of organic materials into soil, such as farmyard manure, is a common practice used by farmers to improve soil fertility (Riley 2007). Furthermore, biochar has been suggested to have a greater potential to increase SOM than other types of organic materials (Rittl et al., 2018). Due to the high carbon content in biochar, which is structurally resistant to microbial decomposition, biochar is expected to remain in the soil for decades. However, biochar is poor in nutrients and hence, mixing it with a nutritious solution such as liquid digestate has been suggested to improve its soil amendment characteristics. Liquid digestate is rich in nutrients and can be used to enrich biochar before soil application. Another option for increasing the SOM is the application of solid digestate, which is produced by separating the residues (digestate) from anaerobic digestion of various organic waste. Solid digestate is rich in organic matter and phosphorus (P).

The application of organic material to soil may be combined with cover crops, especially after growing early potato varieties which are often harvested in early July, leaving the soil open for erosion and nutrient leakage for 3 months or more, depending on the winter conditions. The implementation of these SOM management practices could bring many benefits for the potato production system, such as: greater plant production over time, less land degradation, greater groundwater recharge, less fertilizer use required, lower need for irrigation since the soil’s water-holding capacity may increase, and potentially less presence of soil-borne pathogens and therefore less need for pesticide use. The project MERMOLD (2019-2022) aimed to assess the use of cover crop and organic amendment practices, including biochar and solid digestate, to increase SOM content in the potato cropping systems in this region of Norway.

2 Applied organic materials and their characteristics

2.1 Production

Biochar

Wood chips from Norwegian pine were subjected to pyrolysis at 400°C for 5 minutes (fast pyrolysis) to produce 600 kg of biochar. This was done by Standard Bio AS, at their location in Bø, Telemark. After the producing, biochar was wetted/quenched (approx. 45% moisture content) to avoid combustion.

Solid and liquid digestate

Solid (4000 kg) and liquid digestate (2000 l) derived from sewage sludge, source-separated organic household waste and organic waste from food industry were produced at the facilities of the biogas plant Ecopro AS in Verdal, Trøndelag. After grinding and hygienization of the material at 120 °C, the pulp was anaerobically digested, followed by a mechanical separation into liquid and solid digestate.

Farmyard manure

Solid, relatively fresh horse manure with some sawdust (3000 kg) was collected from a horse stall close to the experimental field, which was located on the farm surrounding the packing plant of Sunndalspotet AS. The horse manure, further called farmyard manure (FYM), was stored uncovered in an outdoor pile prior to this experiment.

2.2 Sampling and analyses

Representative samples (3 litres) of each organic material were stored at 4 °C and sent to EUROFINS, Germany for analysis of potentially toxic elements (PTEs; heavy metals), macro and micronutrients and physiochemical characteristics. The package of analysis has been developed for composts (Eurofins Agro, 2019), and includes analyses of dry matter content, bulk density, loss on ignition, pH (H_2O), total-N, ammonium-N, nitrate-N, total organic C, AL-extractable nutrients, Olsen-extractable P, total P, K, Ca, Mg and Na, micronutrients and PTEs.

In short, samples were dried at 25°C in a well-ventilated room. After drying the samples were grinded in a razorblade mill and sieved (<1.5 mm) and send for posterior analyses. Fresh samples (non-dried) were used for the determination of dry matter content, loss on ignition and bulk density. Dry matter content was determined by drying 100 g of fresh material at 105 °C till constant weight. Loss in ignition was measured by igniting (or heating) air-dried and crushed samples at 450 °C. Compact bulk density was determined by filling a graduated cylinder with fresh material and mechanically tapping it for three minutes before measuring the weight. Bulk density is then calculated from the weight and volume (g cm^{-3}). The pH was determined in water (1:2.5 v/v). Total nitrogen was determined by a modified DIN EN 13654 method and ammonium-N by EN ISO 11732. Elemental analysis was used for total organic C determination. Extractable P, K, Ca, Mg and Na were measured by the ammonium-acetate lactate (AL)-method (standard SS 0283110 +T1), extractable P was also measured by Olsen-P (bicarbonate) method. Total P, K, Ca, Mg, Na, micronutrients and heavy metals were determined using ICP-MS.

Biochar samples not mixed with liquid digestate were sent to the Institute of Physical Chemistry in Ukraine for determination of the specific surface area, the concentration of elements C, H, N, and pH. The specific surface area was determined using the single point Brunauer–Emmett–Teller (BET method) in m^2 g^{-1}. C, H, N concentrations was measured using *Carlo-Erba 1106* elemental analyser.

2.3 Characteristics

The characteristics of applied organic materials are summarized in **Table 1**. The content of total N, ammonium (NH_4-N) and nitrate (NO_3-N) was much higher in solid digestate (SD) than in farmyard manure (FYM). As expected, the total organic carbon (TOC) content of biochar plus liquid digestate (B+LD) was higher than in FYM and SD. Due to the higher N concentration in the SD, the C/N ratio was lowest in this material. The pH was slightly alkaline in all materials, pH 7.6-8. Loss on ignition ranged from 63% for SD to 97% for B+LD. In soil, LOI is used as a proxy for SOM and the relationship with total C is often very close. For these materials, the relationship was weaker, since total C comprised 66% of LOI in B+LD, 40% in FYM and 51% in SD. Extractable phosphorus (P-AL and P-Olsen) was highest for FYM and lowest for B+LD. Total phosphorous was very high for SD, reaching 22 g kg DM^{-1}, but only a minor part of this was extractable. This is likely because of the chemicals (Fe, Al) used to precipitate phosphorus from sewage. SD was also rich in Ca, whereas FYM had the highest concentration of extractable K, Mg, P and Na. The high concentration of easily leachable nutrients such as K in the FYM indicates that the material was relatively fresh, since a long-term outdoor storage would have led to leaching of K. For all materials, the concentrations of PTEs (Cd, Pb, Hg, Ni, Zn, Cu, Cr, As) were below the maximum limits of heavy metals in the Quality Class I of soil amendments specified by the Norwegian authorities (KMD 2022) (**Table 2**), except for Zn and Cd in the SD. With the concentration of Zn being 430 mg kg^{-1} DM, and concentration of Cd being 1 mg kg^{-1} DM, these results placing SD in Class II.

Table 1. Characteristics of the materials applied in the field experiment, *n=1*. B+LD=biochar + liquid digestate; FYM=Farmyard manure; SD=solid digestate. DM= dry matter, ADM= air-dry material

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/100g ADM	6.7	110	45
P-Olsen	mg/100g ADM	3.1	48.7	16.1
Total phosphorous (P)	mg/kg DM	1300	4500	22000
K-AL	mg/100g ADM	310	820	160
Mg-AL	mg/100g ADM	23	99	77
Ca-AL	mg/100g ADM	57	310	1200
Na-AL	mg/100g ADM	160	260	110
Sulphur (S)	mg/kg DM	600	2300	8300
Boron (B)	mg/kg DM	12	11	15
Cobalt (Co)	mg/kg DM	1	2,9	1
Iron (Fe)	mg/kg DM	260	4500	23000
Manganese (Mn)	mg/kg DM	66	250	270
Molybdenum (Mo)	mg/kg DM	2	2	3.5
Cobber (Cu)	mg/kg DM	7	42	180
Zink (Zn)	mg/kg DM	42	150	430
Chloride (Cl)	mg/kg DM	300	6100	1800
Nickel (Ni)	mg/kg DM	5	6	18
Cadmium (Cd)	mg/kg DM	0.1	0.2	1
Lead (Pb)	mg/kg DM	0.3	2	12
Mercury (Hg)	mg/kg DM	0.01	0.02	0.38
Chromium (Cr)	mg/kg DM	6	9	47
Arsenic (As)	mg/kg DM	2	2	4
Total Potassium (K)	mg/kg DM	5300	15000	4900
Total Calcium (Ca)	mg/kg DM	5400	11000	39000
Total Magnesium (Mg)	mg/kg DM	1000	3100	4000
Total Sodium (Na)	mg/kg DM	2300	4600	2800

Table 2. Limits of concentration of potentially toxic elements (heavy metals, mg kg^{-1} DM) allowed in soil amendments and organic fertilizers in Norway (KMD 2022)

Quality classes	0	I	II	III
Cadmium (Cd)	0.4	0.8	2	5
Lead (Pb)	40	60	80	200
Mercury (Hg)	0.2	0.6	3	5
Nickel (Ni)	20	30	50	80
Zinc (Zn)	150	400	800	1500
Copper (Cu)	50	150	650	1000
Chromium (Cr)	50	60	100	150

A surprising result was the specific surface of biochar, which was only 7 m^2 g^{-1}. That value was significantly lower than the 400 m^2 g^{-1} expected for this type of biochar (personal communication with StandardBio). The low specific area was caused by a problem in the oven during production. In spite of the low specific area, the water-holding capacity (WHC) measured in the laboratory was more than 3 times its dry weight, indicating a porous structure (Photo 1). On average (*n=5*), biochar dry weight (105 °C) was 3.7 g, while biochar wet weight (after soaking in water and 4h of free drainage) was 14.9 g. This explains the low value of DM in the B+LD treatment (**Table 1**).

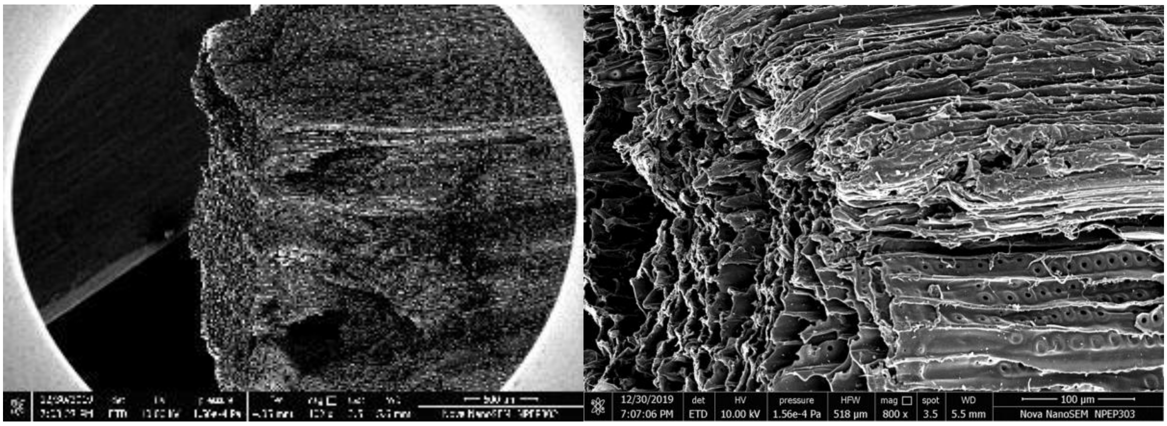


Photo 1. Microscopy images from a pine wood biochar similar to that used in this experiment, showing its porous structure. Photo: StandardBio.

3 Field experiment

3.1 Field experiment design and organic amendment rates

The field experiment was established on 10 July 2019, shortly after the harvesting of early potatoes, on a field belonging to Per Grødal, very near the location of Sunndalspotet AS in Grøa, Sunndal. Experimental plots (3.3 m × 10 m = 33 m^2) were settled in an area infested with silver scurf (*Helminthosporium solani*) and black scurf (*Rhizoctonia solani Kühn*). The experimental design was split-plot in triplicate (**figure 1**). Presence of **winter rye (CC)** and absence of **winter rye (NCC)** was the main factor (plot) and organic amendment (type of organic material applied) the secondary factor (subplot). The organic amendments were application of **biochar with liquid digestate (B+LD), solid digestate (SD)** and **farmyard manure (FYM)**. The total area of the field experiment was 792 m^2.

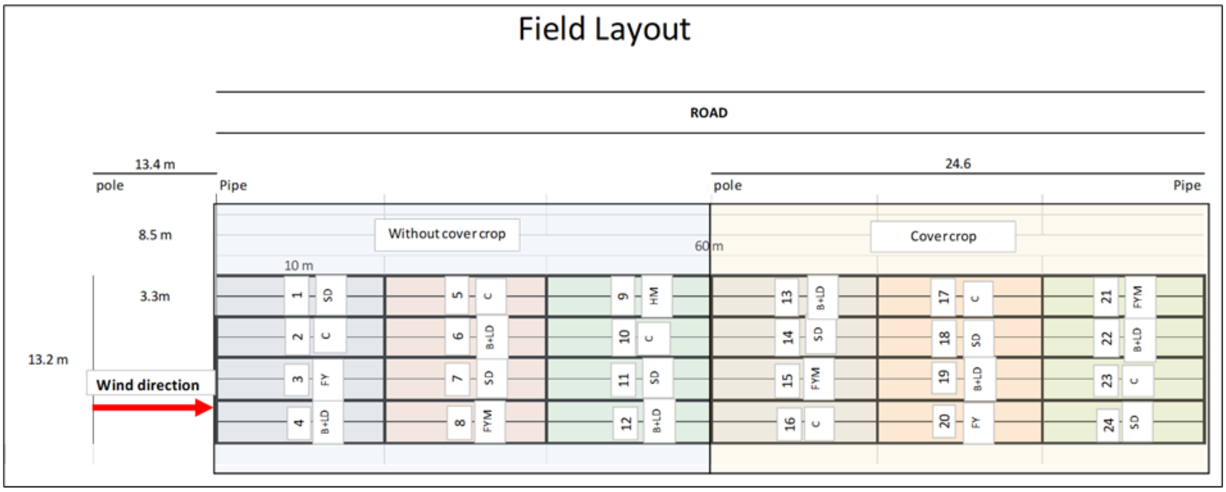


Figure 1. The field layout of the MERMOLD experiment, with a split-plot design with and without cover crop on large plots, and organic amendments on small plots. C= Control, B+LD = biochar + liquid digestate, SD=solid digestate, and FYM = farmyard manure.

Biochar and liquid digestate were mixed on site two hours before the application in field, by a concrete driller (**Photo 2, left side**). The volume of liquid digestate was large enough to allow for a spreading of the B+LD as a slurry (**Photo 2, right side**). Organic materials were applied by hand to the soil on July 10 (**Photo 3**). On July 11, plots were ploughed to a depth of 17 cm to incorporate the materials. Whereas the organic materials were applied only in 2019, cover crop (CC) were sowed on half of the experimental field in 2019, 2020 and 2021 after the harvest of potatoes. Winter rye (100 kg seed grains ha^{-1}) was applied as CC, using the varieties Traktor in 2019, KWS Fabrizio in 2020 and Inspector 2021. In 2019, winter rye started to emerge ten days after sowing at August 2, but did not compete well with the weeds already present in the field, and the CC performed below our expectations. After sowing on July 15 in 2020, and June 30 in 2021, one mechanical weed control was conducted on September 4 in 2020 and August 23 in 2021, which made the CC perform better. The weed was cut by a two-wheel tractor with cutter bar. 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. The winter rye did not survive in any winter. Potato tubers, cv. Solist were planted on April 11-19 in 2020 and April 18 in 2021. 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). For the growing of potatoes, experimental plots were equally fertilized with a complete mineral fertiliser (YaraMila Fullgjødsel 12:4:18 micro) equivalent to 144 N kg ha^{-1} , 48 P kg ha^{-1} and 216 K kg ha^{-1}, and 450 kg ha^{-1} of Polysulphate equivalent to 52.2 K kg ha^{-1}, 54.9 Ca kg ha^{-1}, 16.2 Mg kg ha^{-1} and 86.4 S kg ha^{-1}, to cover the nutrient demand for a normal potato crop in this area. Fertilizer applications were equal across all treatments, so that nutrition would not be limiting in any treatment including the control, and thus treatment effects would likely be related to factors other than fertility.


Photo 2. Left side: Ivar Bakken (Sunndalspotet) mixing biochar and liquid digestate before application in the field. Right side: Liv Solemdal (NORSØK) in the front and Nina Iren Ugelvik (Landbruk Nordvest) in the back applying biochar mixed with liquid digestate. Photo: Tatiana Rittl, NORSØK.


Photo 3. Left side: field experimental plots after application of organic materials on July 10, 2019. Right side: Field experiment after the incorporation of organic materials by ploughing to 17 cm soil depth on July 11, 2019. Photo: Tatiana Rittl (NORSØK).

We aimed for application rates corresponding to 1.5 kg carbon (C) dry matter m^{-2}, to comply with a common rate of biochar application being 15-30 Mg ha^{-1} (Jeffery et al. 2017) as well as the maximal amount of dry matter allowed for the Class I organic soil amendments (KMD 2022), being 40 ton DM ha^{-1} over 10 years. Since the chemical analyses were not available at the set of the experiment, we applied values of C (%) and of dry matter (%) from relevant literature and estimated the amount of C per kg of organic amendment (**Table 3**).

Table 3. Application rates of organic materials, as estimated by literature values

Organic Inputs	Estimated % C in dry matter	% Dry matter	Appl. Rate kg DM/m^2	C kg/m^2	Total fresh matter applied, kg	Reference
B	83	46	1.9	1.5	796	Personal commun. StandardBio
FYM	45	32	3.4	1.5	2111	Chastain et al. 2014
SD	38	28	4.0	1.5	2857	Ecopro, 2009
LD	-	1	-	-	1593*	Ecopro, 2017

*values are in l; biochar (B); liquid digestate (LD); solid digestate (SD) and farm yard manure (FYM).

The total amount of C applied, as calculated from total C analyses (**Table 3**) were somewhat below our goal of applying 1.5 C kg m^{-2}, as shown in **Table 4**. However, the application did not vary too much between the treatments; it was lowest for FYM, followed by B+LD and SD.

Table 4. Estimated *versus* applied total C in the field experiment with the different types of organic amendments

Treatments	Estimated		Applied			
	% C in dry matter	**% Dry matter**	**% C in dry matter**	**% Dry matter**	**Fresh matter kg m^{-2}**	**C kg m^{-2}**
Biochar	83	46	-	-	-	-
B+LD	-	-	64	14	13	1.2
FYM	45	32	32	33	11	1.1
SD	38	28	32	28	14	1.3

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

3.2 Soil and plant analyses

Soil sampling and analyses

Twelve soil cores (0-20 cm) were collected per plot and well mixed and split in two aliquots, before the application of organic materials. One aliquot was dried and stored at room temperature for possibly later analyses. The other was pooled together in one composite sample of the entire field and sent to Eurofins for analyses of PTEs. On July 24, 2019, thirteen days after the incorporation of the organic amendments, and on July 15, 2020 and June 30, 2021 (after potato harvest) one composite soil sample per treatment was collected for chemical analyses, again with 12 soil cores per plot. Samples from 2019 and 2021, were sent to EUROFINS for analysis of AL-extractable nutrients (ammonium acetate lactate method; P, K, Mg, Ca, Na), loss on ignition (to measure soil organic matter) and pH (H_2O). Samples from 2019-2021 were analysed for Active C, and samples 2021 for particular organic matter (POM) and mineral-associated organic matter (MAOM) at NORSØK. Determination of AL-extractable nutrients followed the method developed by Egnér 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 of sieved, air-dry soil is measured by weighing a cylindrical container having a known soil volume which is filled with sieved soil from a fixed height ("shock exposure").

Active C (permanganate oxidable carbon)

The amount of Active C in soil has been suggested as a potential indicator of total SOM, nutrients, soil structure and microbial pools and activity (Bongiorno et al., 2019). Changes in Active C may provide an early indication of improved soil quality in response to addition of organic materials. Active C was analysed following the procedure of Weil, et al. (2003). For that, 20 ml of 0.015 M $KMnO_4$ and 0.1 M $CaCl_2$ was added to the 2.5 g (± 0.3 g) of air dried and 2 mm sieved soil. The tube was shaken for 2 minutes at 200 rpm and thereafter left undisturbed on the lab bench for 10 min to continue oxidation. After 10 minutes, 0.5 ml of the solution was placed in another tube with 30 ml of distilled water. The absorbance of each sample at 550 nm (Abs) was determined using Genesys 50 UV-Vis Spectrophotometer. Oxidation of organic matter will produce a lighter colour.

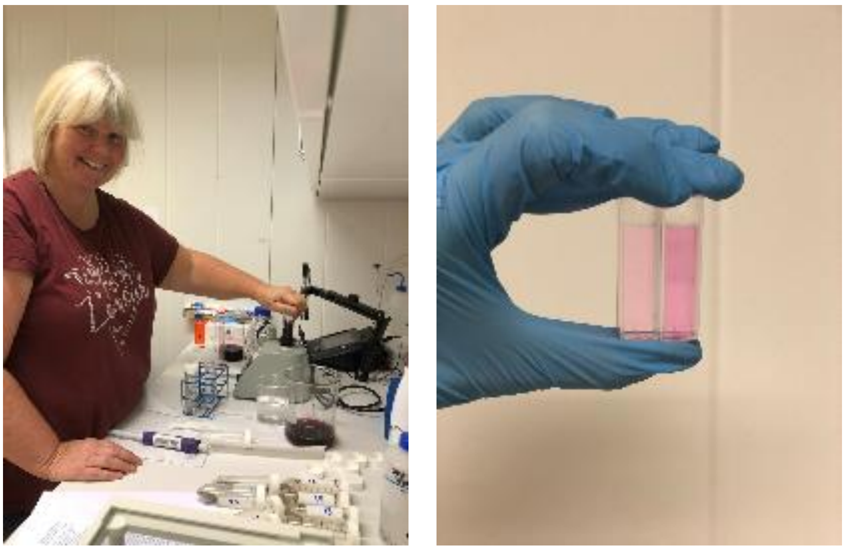


Photo 4. Left side: Peggy Haugnes (NORSØK) measuring Active C in soil from the MERMOLD experiment. Right side: Light purple represents a soil with high content of Active C; dark purple represents a soil with low content of Active C. Photo: Tatiana Rittl, NORSØK.

Soil physical fractionation

Managing soil to effectively sequester C requires a deep understanding of SOM formation, persistence and function. Recently it has been proposed to separate SOM into two functionally distinct soil organic matter physical fractions, particulate organic matter (POM) and mineral-associated organic matter (MAOM) (Lavallee, Soong, and Cotrufo 2019). These fractions are believed to differ fundamentally regarding mechanisms of formation, persistence and their functions in soil. Emerging theory (Cotrufo et al. 2013) suggests that MAOM is most stable and consists of simple molecules that have either been leached directly from plants or organic materials or been chemically transformed by soil biota before becoming associated with soil minerals. By contrast, POM consists of more heterogeneous materials, such as lightweight fragments that are relatively undecomposed (Lavallee, Soong, and Cotrufo 2019), fresh and decomposing organic residues. To increase soil C storage, organic matter management should target the MAOM fraction.

POM and MAOM fractions were analysed in the soil samples from 2021. Prior to laboratory analysis, air-dried soil samples were sieved through a 2 mm sieve. Samples were separated into POM and MAOM using a size-fractionation procedure. For that, 10 g of air-dry and 2 mm sieved soil samples were dispersed in 40 ml 0.5% sodium hexametaphosphate solution (SHMP) for 18h on a reciprocal shaker. Each sample was then washed with distilled water through a 53 µm sieve. The organic material in the soil fraction retained on the sieve was considered the POM, and the finer fraction that passed through the sieve was considered the MAOM. The POM and MAOM samples were dried at 45 °C until constant weight, and weights were recorded. To determine the proportion of SOM in each fraction, the loss on ignition (LOI) was measured in all samples by igniting dried and crushed samples at 550 °C for 4h. POM refers to the OM concentration (LOI%) measured from the >53 µm fraction and MAOM to the OM measured from the <53 µm fraction.

Photo 5. Left side: Scheme to separate POM and MAOM. Middle: Peggy Haugnes (NORSØK) washing the samples with distilled water through a 53 µm sieve. Right side: Samples after wet sieving and before drying. Soil containing mineral associated organic matter (MAOM) on the left side, soil containing particulate organic matter (POM) on the right side. Photo: Tatiana Rittl, NORSØK.

Cover crop sampling and nutrient composition

Cover crops were manually harvested on each experimental plot applying a frame (0.5 m × 0.5 m) inside of which the crop was cut by scissors to a stubble height of about 5 cm, on September 26, 2019, October 18, 2020 and October 18, 2021. Three harvest plot (frame) per experimental plot were combined in one sample and recorded. The fresh weight of plant material was recorded in the field and the material was dried at 40°C until reaching a constant weight for determination of total dry matter (DM%) and yield of CC (g DM/m^2). 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, on a 5 % scale. The proportion of CC coverage was used to calculate the CC dry yield. Plant samples were sent to Actlabs (Canada) for determination of nutrient concentrations (N, P, S, K, Mg, Ca, Na, Fe, B, Cu, Mn, Zn, Al). Nutrients were extracted in an open vessel by a combined nitric acid/peroxide digestion. Total N was analyzed by the combustion method (AOAC 990.03), and P, S, K, Mg, Ca, Na, Fe, B, Cu, Mn, Zn were determined by ICP-OES and Al by ICP-MS.

Photo 6. Left side: Frode Grønmyr (NLR) sowing the winter rye cover crop on July 15, 2020. Middle: emergence of cover crop August 27, 2021. Right side: Frode Grønmyr (NLR) performing the sampling and visual assessment of the cover crop on October 18, 2020. Photos: Tatiana Rittl, NORSØK.

Sampling and analysis of potato petioles

In 2020 and 2021, potato petioles were collected for analyses of full elemental composition to study if the applied organic materials affected differently on the mineral nutrition of the potato plants. In each plot the youngest fully expanded leaf of 30 plants were picked. The leaves were separated from the petiole and discarded. The petioles were dried for 24 hours at 50°C. Plant tissue concentrations of P, S, K, Mg, Ca, N, B, Mn, Zn were analysed by Yara Megalab, UK.

Tuber yield and potato quality assessment

Tuber yields were measured in the harvest plots on June 16, 2020, and June 15, 2021. The harvest plots were 2 rows of potato × 4 m in 2020, and 2 rows × 6 m in 2021. Before harvest the number of potato plants per harvest plot was recorded and applied to correct the yields, when necessary.

Photo 5. Left side: Potato harvest in the MERMOLD field experiment June 16, 2020. Right side: Frode Grønmyr and Hilde Hegnes (Landbruk Nordvest) weighing potato yields on June 16, 2020. Photos: Tatiana Rittl, NORSØK.

A quality assessment of potato tubers to identify the proportion of marketable potatoes was performed in 2020 and 2021 within one week after harvest, and in 2021 also after 4-months storage in a cellar. The quality assessment included a size grading, and a visual quality assessment. In 2020, 5 kg of potatoes per plot were size graded and quality assessed. In 2021, 10 kg of potatoes were size graded and divided into two aliquots of 5 kg. One aliquot was used for the post-harvest assessment and the other was stored for later assessment. Potatoes were size graded in four categories: < 40 mm, 40-50 mm, 50-60 mm, > 60 mm. The fresh weight of each category was recorded. Potatoes sized 40-50 mm were visually assessed and classified in seven categories, where six were sorted out due to various diseases or other defects, and the remaining tubers were marketable potatoes. If skin disease covered > 10% of the potato surface, the potato was sorted out and classified with one of the following diseases or defects: silver scurf, black scurf, skin spot, growth cracks, green skin, and blemishing. Marketable potatoes were the tubers being 40-50, with no quality defects.

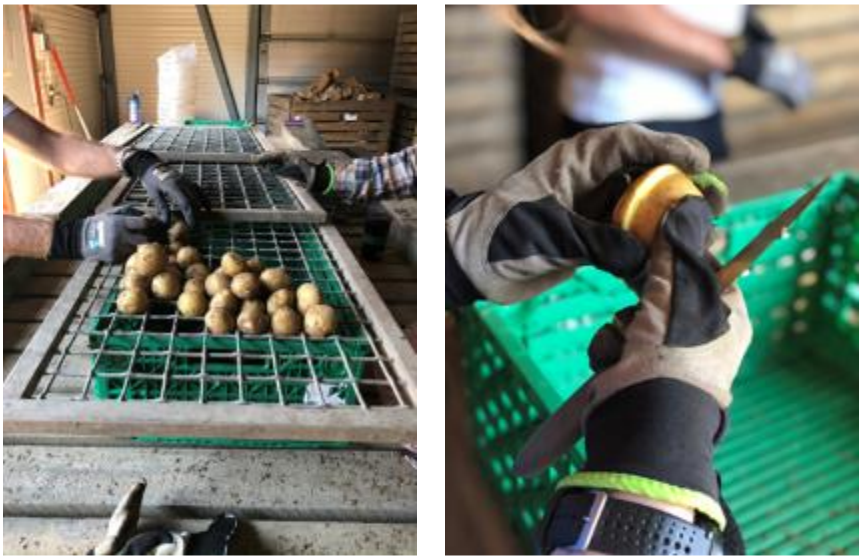


Photo 7. Left side: Size-grading potatoes from the MERMOLD experiment on June 26, 2020. Right side: visual assessment of potato quality in the MERMOLD project on June 26, 2020. Photos: Tatiana Rittl.

3.3 Statistical analyses

Analyses were performed with Minitab Statistical Software. We used variance analysis applying a general linear model (GLM) to compare the effect of organic materials and cover crop treatment on soil characteristics and nutrient concentrations in potato petioles. Organic materials (No OM (Control), B+LD, SD, FYM) and cover crop (CC, NCC) were the fixed factors, and year and/or subplot (for OM) were covariates. OM effects on soil characteristics were analysed for both years 2019 and 2021, while the effect of CC and the interaction effect between CC and OM on soil characteristics were only checked in 2021. We tested the effect of OM on the cover crop yield by one-way variance analysis (ANOVA) for each year. Differences in the potato yield and potato quality caused by organic amendments and cover crop were tested by variance analysis (GLM) for each year, with organic material and cover crops as fixed factors. When no significant interaction between OM and CC (CC × OM) was found, results were presented as main effects of OM and CC. Effects of treatments were considered statistically significant at $p < 0.05$. Significant differences between mean values were then detected, using Tukey t-test.

The SOC stocks in 0-20 cm soil layer were calculated as follows:

SOC (Mg ha^{-1}) = (Loss of Ignition (%) – correction for clay content) × 0.5 (conversion factor for SOM) × bulk density (kg l^{-1}) × soil depth (cm)

The correction for clay content compensates for the loss in weight during loss on ignition, due to 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).

3.4 Results

Initial concentration of potentially toxic elements in the field experimental soil

As shown in **table 5**, the soil on the experimental field had concentrations of potentially toxic elements (PTEs) well below the limits stated in the national regulation on organic fertilisers and soil amendments (KMD 2022). The concentrations of nickel and copper were nearest to the limiting values.

Table 5 Concentration of potentially toxic elements in the experimental soil (*n=1*) as compared with maximum values permitted for soil where organic materials of quality class I or II shall be applied (KMD 2022)

Element	Unit	Values	Limits set in Norwegian regulations on fertilisers of organic origin
Arsenic (As)	mg/kg DM	<2.0	-
Lead (Pb)	mg/kg DM	5	50
Cadmium (Cd)	mg/kg DM	0.2	1
Copper (Cu)	mg/kg DM	14	50
Chromium (Cr)	mg/kg DM	16	100
Mercury (Hg)	mg/kg DM	0.05	1
Nickel (Ni)	mg/kg DM	9	30
Zink (Zn)	mg/kg DM	28	150

Winter rye yield and nutrient composition

The biomass of CC with weeds was larger in 2021 than in 2019. In 2020, it was very low. The total fresh or dry weight was not significantly higher in any treatment where organic materials were applied in any year, but these amendments seemed to favour the growth of the cover crop since in all years, the proportion of CC in the biomass was higher with application of OM. Across 2019-2021, the CC yield was highest in the SD treatment, followed by B+LD, FYM and Control (**Table 6**).

Table 6. Total fresh and dry weight of the CC canopy, % of coverage by the cover crop (CC)and cover crop dry weight measured in the MERMOLD field experiment.

Year	Treatment	Fresh weight (g m^{-2})	Dry weight (g m^{-2})	CC %	CC dry weight (kg DM CC ha^{-1})
2019	No OM	460	113	21	235
	B+LD	533	119	35	417
	FYM	330	93	34	316
	SD	654	124	43	535
2020	No OM	86	40	25	100
	B+LD	114	45	37	166
	FYM	79	44	42	183
	SD	136	50	37	184
2021	No OM	1007	118	17	197
	B+LD	924	108	33	360
	FYM	992	113	27	300
	SD	1125	141	50	707

The concentrations of macronutrients in the CC canopy were higher in the B+LD and SD treatments than in Control and FYM in 2019 (**Figure 2**). In later years, the organic material treatments did not affect notably on the macronutrient concentrations. For the concentration of the micronutrients B, Cu, Fe, Mn and Zn, and of Na and Al which should not be present in high concentrations, the values were generally little affected by the organic amendments. Iron (Fe) comprised the largest proportion of these microelements, and Al the second largest.

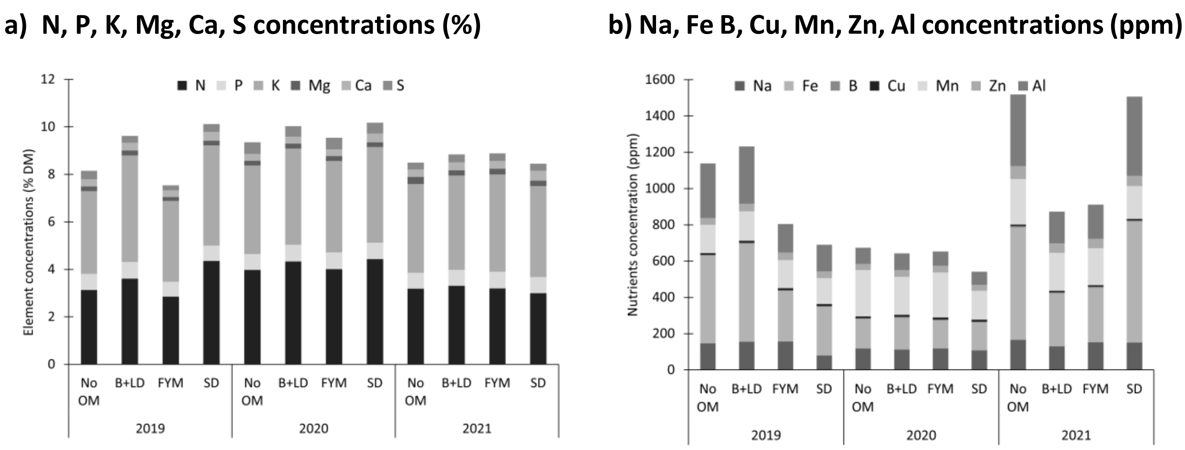


Figure 2. Element concentrations in the catch crop canopy in 2019-2021 in treatments receiving application of organic materials in 2019, compared with a control with no organic material application.

Soil characteristics

The organic amendments had a significant effect on some soil characteristics as recorded 13 days after application (**Table 7**). The loss on ignition was higher in FYM than in the Control. In spite of the significantly higher pH in the organic materials than in the experimental soil (7.6-8, **Table 3**), the soil pH increased very little. Concentrations of P-AL increased slightly with FYM and SD. Whereas Mg-AL and Ca-AL were not affected, the AL-extractable concentrations of monovalent cations K and Na increased with application of all organic materials, with FYM showing the highest values. The same pattern was found in 2021, when in June 20, 2021, FYM treatments showed a higher value of Na-AL, Mg-AL, K-AL than SD and B+LD both with and without cover crop. Also for B+LD, P-AL increased in both systems. The LOI values were slightly lower in 2021 than in 2019 in all treatments, and CC did not increase the LOI in soil. Yet, the LOI values were higher in all treatments receiving organic materials in 2019 than in the unamended control, and the increase in LOI was highly significant (**Table 7**).

Table 7. Mean values of soil characteristics as affected by the application of organic materials (OM) on July 11, 2019; assessed on July 23, 2019 and June 30, 2021. CC = cover crop, NCC = no cover crop, Organic amendments comprised Control; B+LD=biochar + liquid digestate; FYM=farmyard manure; SD=solid digestate

Year, CC, OM	Ignition loss	pH	P-Al	K-Al	Mg-Al	Ca-Al	Na-Al
	% dry soil	H_2O	mg/ 100 g soil dry weigh				
				2019			
2019 average	2.58	5.30	17.75	10.33	5.67	37.04	4.13
Control	2.47	5.27	17.67	8.67	5.33	34.67	2.67
B+LD	2.58	5.23	17.17	9.83	5.67	37.00	4.83
FYM	2.73	5.42	18.17	12.17	5.83	36.33	5.33
SD	2.52	5.30	18.00	10.67	5.83	40.17	3.67
				2021			
2021 average	2.41	5.12	19.96	9.50	5.92	39.54	3.56
NCC average	2.39	5.08	21.50	9.67	5.83	38.42	2.79
Control	2.27	4.93	20.67	8.67	4.67	34.67	2.60
B+LD	2.47	5.00	23.33	10.00	6.00	36.67	1.97
FYM	2.47	5.13	19.67	10.33	7.00	39.67	3.63
SD	2.37	5.23	22.33	9.67	5.67	42.67	2.97
CC average	2.43	5.17	18.42	9.33	6.00	40.67	4.33
Control	2.33	5.10	17.67	9.33	6.00	38.67	3.33
B+LD	2.47	5.10	19.67	9.33	5.33	37.67	3.97
FYM	2.50	5.13	18.33	10.33	7.00	40.33	5.67
SD	2.43	5.33	18.00	8.33	5.67	46.00	4.33
				P-value			
CC (2021)	0.144	0.550	**0.017**	0.183	0.751	0.697	0.074
OM (2019 and 2021)	**0.000**	**0.027**	0.826	**0.001**	0.057	**0.003**	**0.019**
CC vs OM (2021)	0.944	0.781	0.877	0.543	0.599	0.886	0.833

Table 8. Mean values in 2021 of soil organic carbon (SOC) stocks in treatments that received a single application of organic materials (OM) in 2019 and in the plots with and without cover crops (CC). Different letters indicate statistically significant differences (n=6) ($P < 0.05$) between the different types of OM or presence/absence of CC. % of change calculated in relation to the Control and treatment without cover crop

Treatments	SOC stock (ton ha^{-1})		% change
No organic amendment (Control)	30	b	-
Biochar mixed with liquid digestate	32	ab	7.3
Farmyard manure	32	a	8.0
Solid digestate	31	ab	4.4
No cover-crop	31	-	-
Cover crop	32	ns	1.7

The SOC stocks in 2021 were higher in the treatments that received organic materials in 2019 than in the Control. The increase in SOC stock level was about 4%, 7% and 8% for the SD, B+LD and FYM treatments compared to the Control. For the CC, there was no significant differences between the treatments with and without cover crop.

Active C

The amount of Active C was not significantly affected by the application of different organic materials or by the presence of cover crops (CC). Even if the trend was mostly an increase, the increase was statistically significant only in the B+LD treatment (**Figure 3**). The average amount of Active C in the soil across all treatments was 199 mg C kg^{-1} soil in 2019 and 223 mg C kg^{-1} soil in 2021. For the treatments, across all the years, the average values of active C were: 199 mg C kg^{-1} soil for no OM; 210 for B+LD, 217 for FYM and 227 for SD. For NCC and CC, the average values across the three years, were 211 and 215 mg C kg^{-1} soil.

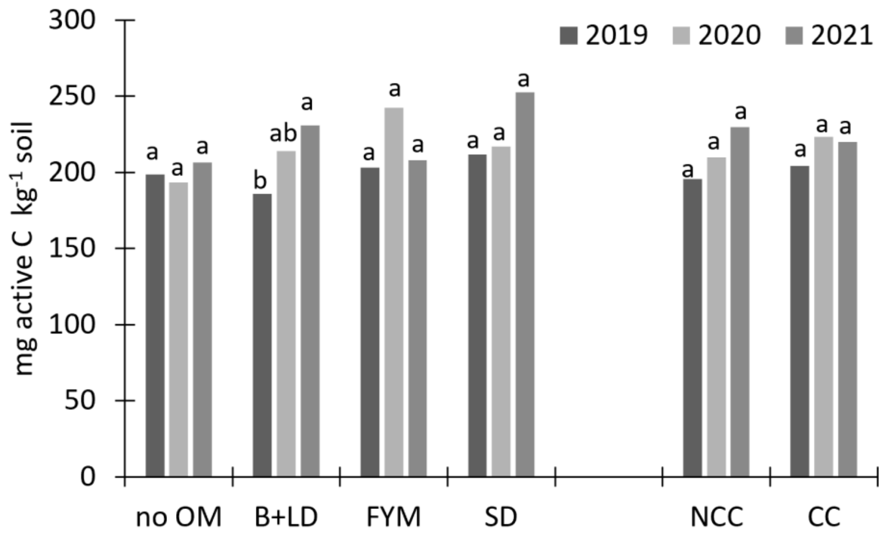


Figure 3. Concentration of Active C (permanganate oxidable carbon) in the topsoil (0-20 cm) over the experimental years in treatments amended with organic materials in 2019. no OM = no organic amendment (Control); B+LD= biochar mixed with liquid digestate; FYM= farmyard manure; SD= solid digestate. NCC= no cover crop; CC= cover crop. Different letters indicate statistically significant differences across years within each treatment ($P < 0.05$).

POM and MAOM

After drying of the 53 µm wet-sieved soil samples, the proportion of the fraction >53 µm was about 84%, whereas about 13% had passed the 53 µm sieve, across all treatments (**Figure 4**). A small proportion of soil, 1-4%, was lost in the procedure. The differences between treatments with respect to the amount of soil being > or < 53 µm were small and not statistically significant.

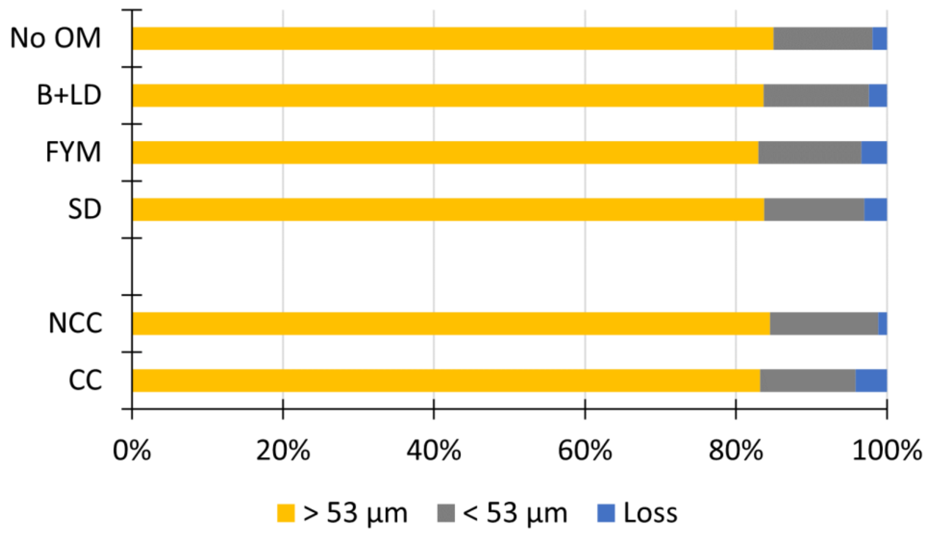


Figure 4. Mean proportions of soil recovered in the fractions >53 µm and <53 µm after wet-sieving and drying, and loss of soil during the fractionation depicted for each treatment (see Materials and Methods for explanations of abbreviations).

The concentration of OM in the mineral-associated organic matter (MAOM), being protected, ranged from 0.95 to 1.27 %, as assessed by loss on ignition (LOI). For the unprotected type, being particulate organic matter (POM), the concentration of OM ranged from 0.10 to 0.41%. Application of organic materials in 2019 increased the POM as compared with the Control, by 54% for B+LD, 33% for FYM and 18% for SD. POM was about 4% higher with CC compared to the NCC treatments. For MAOM, the effect of organic material application in 2019 was neglectable. The use of CC reduced MAOM by 7% (**Table 9**).

Table 9. Ignition loss (%) of fractions of soil wet-sieved at 53 µm for soil amended with different types of organic material in 2019, and the change in POM and MAOM as compared with the Control (No OM, NCC).

Treatments	**LOI (%)**		**% change in relation to the Control**	
	POM (>53 µm)	**MAOM (<53 µm)**	**POM (>53 µm)**	**MAOM (<53 µm)**
No OM	0.20	1.11	-	-
B+LD	0.31	1.12	54	1
FYM	0.26	1.14	33	3
SD	0.23	1.09	18	-1
NCC	0.25	1.15	-	-
CC	0.26	1.07	4	-7

Organic matter stabilization in soil is ultimately governed by physicochemical protection mechanisms operating within the mineral soil matrix, and therefore this measure will become saturated over time (Castellano et al. 2015). The test soil had a low clay content, which fits with the result that application of organic materials did not increase MAOM, but POM only. The soil texture will affect both the absolute and the relative amount of POM and MAOM. Once the MAOM is saturated, organic materials applied to the soil will accumulate as POM (Lavallee, Soong, and Cotrufo 2019). Here, we could not distinguish between the native SOM and POM or MAOM recently applied by OM inputs or cover crop.

Potato petioles

The potato petiole concentrations for the major nutrient elements (N, P, K) were within the normal (sufficient level) ranges (Agyarko et al. 2006) for all treatments, while Ca and Mg were below the sufficient level ranges. This indicates a too low soil pH and a too high K-fertilization which may have resulted in a low uptake of Mg and Ca by the plants. A suboptimal concentration of these nutrients can cause reduced tuber size and number and increase the incidence of potato diseases (El-Hadidi et al., 2017). Application of organic materials affected on the concentrations of Ca and P, with more Ca but less P in petioles from potatoes grown in soil amended with SD. Application of FYM in 2019 increased the concentration of K in the petioles.

Table 10. Element concentrations in the potato petioles in June 2020 and 2021 in treatments receiving application of organic materials in 2019, % or ppm of plant DM. No OM = Control with no organic material; B+LD= biochar mixed with liquid digestate; FYM= farmyard manure; SD= solid digestate. Threshold values of sufficient nutrient concentrations refer to (Agyarko et al. 2006)

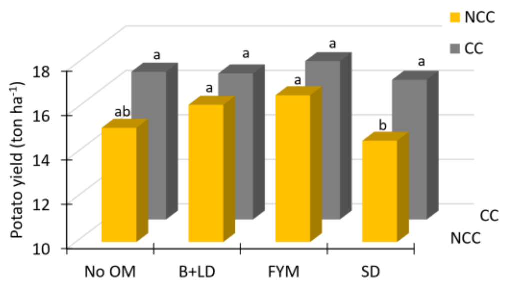
Year, CC, OM	**Ca**	**Mg**	**S**	**P**	**K**	**Mn**	**B**	**Zn**	**NO_3**
		____________%___________				____________ppm___________			
					2020				
2020 average	0.24	0.22	0.35	0.53	8.07	105.51	21.03	45.14	18.82
NCC average	0.25	0.20	0.35	0.53	8.21	114.83	21.78	48.21	19.56
Control	0.21	0.20	0.39	0.53	8.13	131.00	22.00	50.30	19.96
B+LD	0.20	0.20	0.35	0.55	8.57	115.23	22.60	48.93	19.33
FYM	0.20	0.20	0.33	0.54	8.19	106.50	21.50	49.57	19.66
SD	0.38	0.20	0.33	0.50	7.97	106.57	21.00	44.03	19.33
CC average	0.24	0.24	0.35	0.52	7.93	96.19	20.28	42.08	18.14
Control	0.21	0.27	0.34	0.52	7.84	100.40	20.90	41.90	18.03
B+LD	0.22	0.23	0.38	0.53	7.96	108.80	20.50	43.40	17.44
FYM	0.20	0.20	0.35	0.53	8.35	87.00	20.13	43.43	17.81
SD	0.32	0.27	0.34	0.51	7.55	88.57	19.60	39.57	19.86
					2021				
2021 average	0.23	0.14	0.37	0.45	8.62	138.83	19.37	33.38	12.34
NCC average	0.23	0.14	0.38	0.45	8.70	145.83	19.58	35.13	11.77
Control	0.21	0.17	0.43	0.46	8.41	194.33	19.63	38.23	11.18
B+LD	0.21	0.13	0.37	0.46	8.81	134.10	19.77	35.07	12.11
FYM	0.19	0.17	0.38	0.47	9.11	127.90	18.77	33.23	11.75
SD	0.31	0.10	0.34	0.39	8.48	126.97	20.13	33.97	12.05
CC average	0.23	0.13	0.36	0.45	8.53	131.83	19.16	31.64	12.91
Control	0.20	0.17	0.36	0.45	8.79	127.43	19.17	32.63	13.58
B+LD	0.21	0.13	0.40	0.47	8.26	147.53	19.00	31.53	12.19
FYM	0.19	0.13	0.36	0.49	8.48	129.07	19.03	31.23	12.44
SD	0.31	0.10	0.32	0.39	8.58	123.30	19.43	31.17	13.44
Threshold values	***0.60***	***0.30***	***0.20***	***0.22***	***8.00***	***30.00***	***20.00***	***20.00***	***11.00***
					P-value				
Year	0.196	**0.000**	0.151	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
CC	0.303	0.210	0.329	0.911	0.052	**0.008**	**0.000**	**0.004**	0.997
OM	**0.000**	0.316	**0.032**	**0.002**	**0.000**	**0.006**	0.061	0.460	0.585
CC vs OM	0.404	0.495	0.067	0.902	0.126	**0.018**	0.578	0.782	0.544

Tuber yield, marketable potatoes and potato quality

There was no significant interaction between application of organic material and use of cover crop (OM x CC) on the tuber yields or quality of the tubers. Hence, the results are presented as main effects of OM and CC. The average tuber yield across all treatments and years was 16 tons ha^{-1}, which was lower than the yields the farmer usually achieves, due to early harvest.

On average (2020-2021), the tuber yield and the yield of marketable potatoes were 15.6 ton ha^{-1} vs. 11.5 ton ha^{-1} for NCC treatments, and 16.7 ton ha^{-1} vs. 13.4 ton ha^{-1} for the CC treatments (**Figure 5)**. The differences between organic material treatments were mostly not statistically significant, but on average the FYM treatment had the highest tuber yields and yield of marketable potatoes, followed by B+LD. The treatment with SD had similar yields to the Control plot (no OM).

a) Tuber yield



b) Marketable potatoes

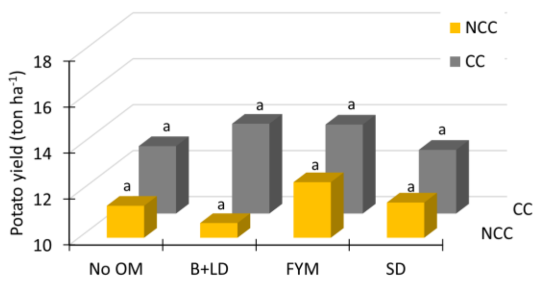


Figure 5. Average yields (2020-2021) of a) total potato production (ton ha^{-1}) and b) marketable yields (ton ha^{-1}) for the treatments with various organic materials (OM), with cover crop (CC) or without cover crop (NCC). Within each CC treatment (NCC, C), different letters indicate statistically significant differences between OM treatments (P < 0.05).

The amount of marketable potatoes was higher in the treatments with FYM and B+LD than in the Control, while the CC had 9% more marketable potatoes than NCC treatments (**Table 11**). Difference among treatments became more evident after four months of storage, when the total of marketable potatoes reduced to all treatments compared to the results of the post-harvest assessment. B+LD, FYM, SD had respectively 11%, 22% and 11% more marketable potatoes than the No OM, and CC treatments had 37% more marketable potatoes than NCC treatments **(Table 11**). In former studies, improvements in soil conditions due to CC and OM have been associated with increases in yield and quality of potato tubers across different systems (Larkin et al. 2017; Larkin et al. 2021; Larkin et al. 2010).

Table 11. Total yields of potato tubers (tons ha^{-1}) and marketable potatoes (ton ha^{-1}) shortly after manually harvest and after 4 months of storage in 2021.

Treatments	Tuber Yield	NCC Marketable potatoes After harvest	NCC Marketable potatoes After storage	CC Tuber Yield	CC Marketable potatoes After harvest	CC Marketable potatoes After storage
			2020			
Mean 2020	**15.7**	**13.1**	**_**	**16.4**	**14.3**	**_**
No OM	15.7	14.5	_	16.2	13.2	_
B+LD	15.0	10.7	_	17.1	15.3	_
FYM	17.0	13.8	_	16.2	15.0	_
SD	15.0	13.2	_	16.1	13.6	_
			2021			
Mean 2021	**15.6**	**13.1**	**8.3**	**16.8**	**14.3**	**11.5**
No OM	14.8	12.8	6.8	16.9	14.3	11.3
B+LD	16.8	13.6	7.7	16.3	14.4	12.0
FYM	16.4	13.7	9.7	17.6	14.5	12.0
SD	14.3	12.3	9.1	16.4	13.9	10.8
			P-values			
	Tuber yield			Marketable potatoes		After storage
			2020			
CC	0.728			0.415		-
OM	0.395			0.112		-
			2021			
CC	0.038			0.130		0.035
OM	0.035			0.419		0.443

The size distribution of potatoes was quite different in 2020 and 2021 (**Figure 6**). The proportion of potatoes being too small for marketing (< 40 mm) was considerably higher in 2021. In both years, the proportion of tubers being above marketable size (> 60 mm) was negligible. Potatoes between 40 and 50 mm comprised the largest proportion of the potatoes which were marketable with respect to size in both years, but more potatoes were 50-60 mm in 2020. Whereas the organic amendments did not affect significantly on the size grading results, the use of CC seemed to reduce the proportion of small potatoes (< 40 mm), and hence increase the marketable yield.

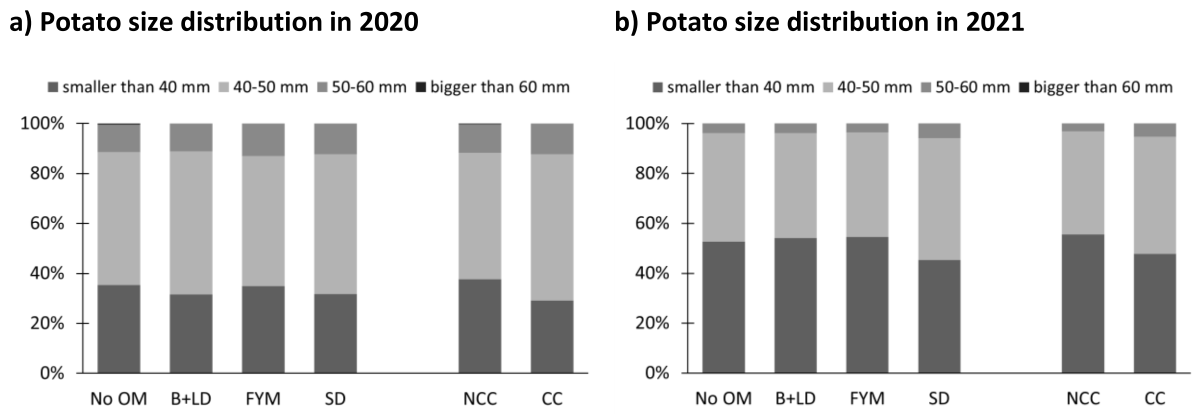


Figure 6. The distribution of potatoes (%) in different sizes in the treatments in the two growing seasons.

From the quality assessment of diseases and defects in of tubers sized 40-50 mm, deformed potatoes and potatoes with other defects were the main problems identified in 2020, whereas black scurf affected a significant proportion of potatoes in 2021 (**Figure 7 and 8**). Other defects include potatoes with discoloration covering more than 10% of the tuber surface, dry frost damage, snail or larval gnaw that is deeper than 5 mm, weed root in the potato tuber, internal discoloration, and central necrosis. Deformed potatoes are potatoes that deviated from their typical form, with growth over 10 mm. Deformed potatoes may also be an early symptom of black scurf which may develop during storage. The results varied between assessment dates, but in general the reasons for sorting out the potatoes did not differentiate between the presence and absent of CC. For the different types of OM, SD treatments had a large % of potatoes infected with black scurf after harvest 2021.

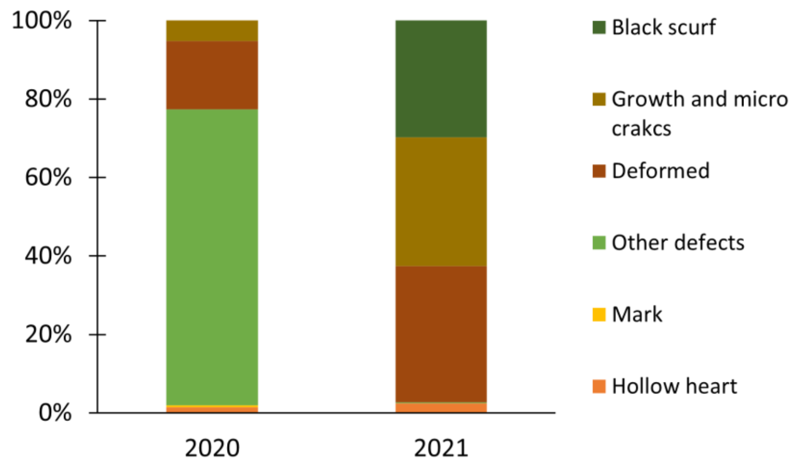


Figure 7. Proportions of potatoes (40-50 mm) being sorted out due to various quality defects in 2020 and 2021 (%).

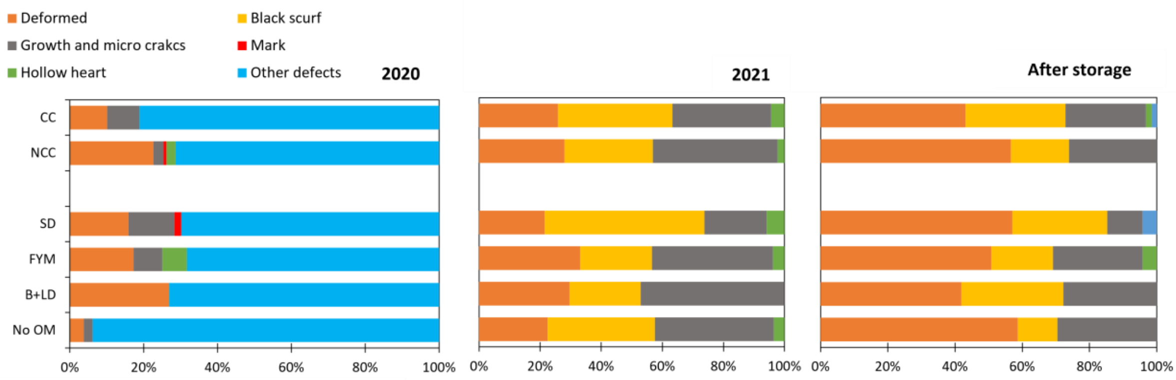


Figure 8. Quality defects (% of total sorted out) identified in the potatoes (40-50 mm) in 2020 and 2021 in treatments where organic materials (OM) were applied in 2019 compared with a Control (No OM), with (CC) or without cover crop (NCC). After storage = new assessment after 4 months of storage in 2021.

4 Decomposition dynamic of the organic materials

A PASCO wireless CO_2 sensor was applied to measure CO_2 emissions from mixtures of experimental soil and organic materials applied in the field experiment. The CO_2 sensor provides a real time measurement which allows for detecting and correcting any abnormality faster.

4.1 Materials and Methods

Design of the incubation experiment

The experiment was composed by 6 treatments and one Control. The treatments consisted of the three types of organic material applied in field (B+LD, FYM and SD) × 2 application rates (low and high). High-rate treatments (H) were equivalent to the application rates used in the field experiment, and low-rate treatments (L) were half of those used in the field experiment (Table 4). For the experiment, 75 g of sieved (< 2 mm) and air-dry soil plus 0.75 or 1.5 g of B+LD per bottle, 2.35 or 4.7 g of HM per bottle and 1.8 or 3.6 g of SD per bottle were filled in incubation jars (250 ml volume) and thoroughly mixed. For Control treatments, only soil was used. The moisture of the soil and soil-OM mixture in the jars was adjusted to 60% of the maximum water holding capacity as measured with similar amounts of soil and organic material (see below) 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 events simulating freeze-thawing which would typically occur under Norwegian winter conditions, on days 265, 288, 330 when samples were frozen to -20 °C and gently thawed in a water bath. All treatments were replicated four times (n=4).

Measurement of CO_2

Soil respiration was measured using the wireless Pasco CO_2 sensor, where CO_2 concentration is measured as the amount of infrared energy absorbed by CO_2 gas. 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 the mobile phone using the SPARKvue software. CO_2 measurements were performed during 3 minutes with one measurement of CO_2 every 15 seconds, resulting in 12 CO_2 measurements per bottle per sampling day. CO_2 concentrations were calculated on a per g of soil basis, and expressed per g of air-dried dry soil.

Microbial carbon content, fungi and bacteria ratio

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 1 g of soil was dispersed with reagents, and the microbial carbon content (µg C g soil $^{-1}$) and ratio of fungi and bacteria quantified by colour using microBIOMETER® app.

Water holding capacity (WHC)

Water holding capacity was measured for the soil and soil mixed with organic materials. For that 30 g of soil or soil mixed with the organic materials at the same rate as used in the incubation were added to a funnel plugged with cotton. Thereafter, the soil or amended soil was saturated with 100 ml of deionized water and allowed to freely drain until no further water loss (approx. 4h) occurred. Samples were then weighed, oven dried at 105 °C for 24h and weighed again, for determination of water content. We used three replicates per treatment for determination of the WHC.

Statistical analyses and calculations

We calculated the relative contribution of each type of organic material (OM) to the CO_2 emissions by subtracting the emissions of the Control (only soil) from the mixture of OM + soil. The relative decomposition rate (k) of OM was estimated using the formula $k= - (\ln C_f - \ln C_i)/ (t_f - t_i)$, where C_f is the remaining OM-C content (g C m^{-2}), C_i is the initial OM-C (g C m^{-2}) and $t_f - t_i$ is the total days of the experiment. C_f was estimated by subtracting the cumulative emitted CO_2-C from the initial OM-C content. Half-life (HL) and mean residential time (MRT) in years of the OM was estimated using the formula $HL= \ln(2)/k$ and $MRT=HL/\ln(2)$.

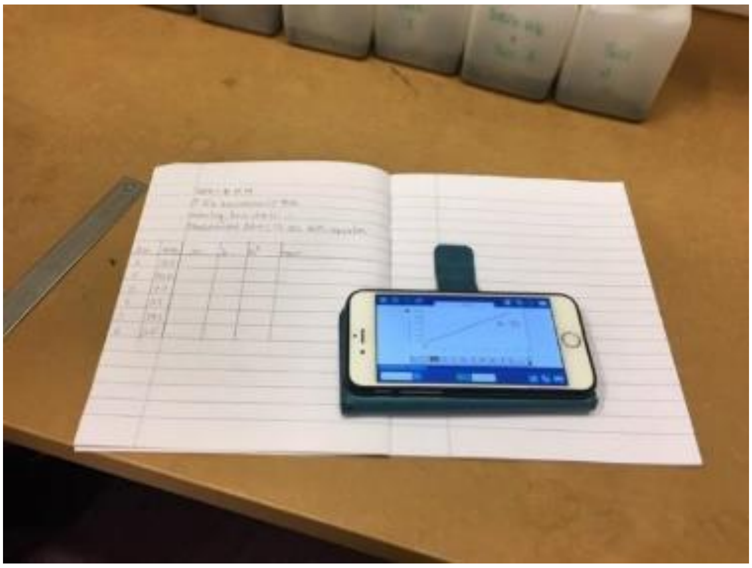


Photo 8. Left side: Pasco wireless CO_2 sensor during measuring the increase in CO_2 concentration inside a bottle with soil. Right side: Real-time measurement displayed on the mobile screen. Photos: Reidun Pommeresche, NORSØK.

4.2 Results

CO_2 flux

Soil CO_2-C fluxes, an indicator of microbial activity, decreased over time in all treatments, except for the Control which had a very stable and low CO_2 emission. Soils amended with OM had larger CO_2 fluxes than the Control during the first weeks of the experiment, but this effect diminished with time (**Figure 7**). Cumulated CO_2 fluxes for the first 100 days of incubation varied from 19% of the total CO_2-C emitted for the low-rate B+LD treatment to 54% of the total CO_2-C emitted for the high-rate SD treatment. At the end of the first year, cumulated CO_2 fluxes varied from 57% of the total CO_2-C emitted for the low-rate B+LD treatment to 78% of the total CO_2-C emitted for the high-rate SD treatment. In our study, C loss as CO_2 originating from OM ranged from 6 to 27% of the total C added with B+LD, 21 to 25% for FYM and 47 to 49% for SD. These results indicate that part of the OM, even applied as biochar, is biologically available and can be degraded by soil microorganisms. Emissions increased after the first freeze-thaw event for the treatment with high rate of B+LD application, but not so much for the other treatments. After the second and third freeze-thaw event, there were no significant effects on subsequent CO_2 emissions.

a) Daily CO_2 fluxes **b) Accumulated CO_2 fluxes**

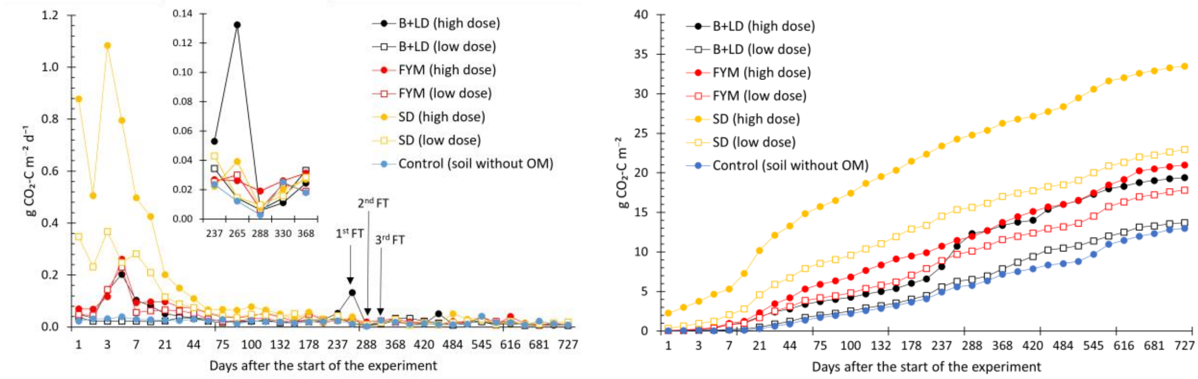


Figure 9. a) Daily CO_2-C fluxes from soil treated with different types and rates of organic material (OM) and a Control (soil only), arrows indicate three freeze-thaw (FT) events. The inserted graphic is a close-up of the emissions during the 1st FT event. b) Cumulative CO_2-C emissions.

The decrease of CO_2 fluxes after 20 days for B+LD and FYM observed in our studies is likely related to the quick initial decomposition of some labile compounds in these materials. SD seems to have a larger pool of labile compounds, leading to smaller, but more long-lasting CO_2 fluxes (**figure 9)**. The C:N ratios of the OM investigated in this study did not appear to be the main drivers of their mineralization. B+LD and FYM had similar C:N ratios (**Table 2**) but had different mineralization rates (-k), resulting in different mean residential time (MRT). The mineralization rates ranged from 0.031 for the low-rate B+LD to 0.334 for the high-rate SD (**Table 13**), leading to a MRT of 3 years for SD, 7-8 years for FYM HM, and 6-32 years for the low and high rates of B+LD. The low rate of FYM showed a slightly higher decomposition rate than the high rate FYM. This may be due to some effect of a high dose of FYM in the microbial community, as the FYM high rate showed a lower amount of microbial carbon and percentage of fungus than the other treatments (**Figure 10**). It should be noted that the relative decomposition rates, half-life and mean residence times are only estimations, and they should not be used to predict what could happen with real conditions in field. Nevertheless, the differences between the decay rates suggested that the application of B+LD has a higher potential to sequester C into a sandy soil as compared with FYM and SD.

Table 13. Mineralization rate (-k), half-life and mean residence time (MRT) of different organic materials (OM) assessed in a 727-day incubation study.

OM	Applied rate	(-k)	Half-life (years)	MRT (years)
B+LD	High	0.155	4	6
	Low	0.031	22	32
FYM	High	0.118	6	8
	Low	0.147	5	7
SD	High	0.334	2	3
	Low	0.321	2	3

The microbial carbon content (MBC) and the proportion of fungi and bacteria (%) did not significantly differ between treatments (p=0.101 and p=0.253) after 727 days of incubation (**Figure 9**). Yet, they were higher in the treatments with OM than in the Control (soil only). The MBC varied from 679 µg C g soil^{-1} for the Control to 1292 µg C g soil^{-1} for the low FYM treatment. There was a big difference between the treatments with high and low rates of FYM, but not so much for the other treatments. The percentage of fungi was higher in the treatments with addition of OM than in the Control.

a) Microbial carbon content (MBC) **b) % of fungi vs. bacteria**

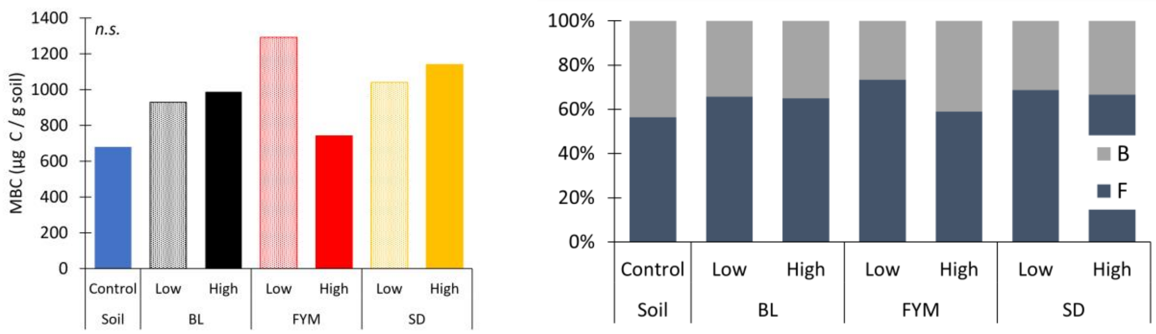


Figure 10. Microbial carbon content (MBC) and the ratios of fungi vs. bacteria (%) after 727 days of incubation in soil amended with different types and rates of organic materials.

The persistence of organic matter in soil is a characteristic determined by several soil and climate characteristics and may be referred to as an ecosystem property. In sandy soil, organic matter is less protected in soil aggregates and clay-humus associations. Therefore, the organic matter is more exposed to decomposition, with increased decomposition rates as compared with soils with a finer texture. Hence, the biochar applied was less protected from decomposers by fine-sized mineral particles than would have occurred in a more finely textured soil. The mixing of biochar with liquid digestate reduced its C/N ratio and may also have affected the rate of decomposition. Furthermore, during the incubation study, we performed 3 freeze-thaw events, where the first affected the decomposition of B+LD. Recalcitrant C is known to be more susceptible to increase in soil temperature. Indeed, we observed a higher emission of treatment with high-biochar rate during this experiment. Rittl et al. (2020) also observed relative increases in soil CO_2 emissions from biochar-amended soils when increasing the temperature from 20 to 30 °C. Nguyen et al. (2010) reported higher Q_{10} values (increase in the decomposition rate with 10 °C increase in temperature) and recalcitrant C in oak-biochar produced at 600 °C than in corn-biochar produced at 350 °C, as well as higher levels of labile

C when incubated in a pure sandy matrix, increasing biochar decomposition from 4.6% to 14.6% within one year for the temperature range of 4 °C to 30 °C. Biochar is more susceptible to changes in temperature than ordinary organic matter. Thus, not only the quality and quantity of the organic input but also the soil and climatic conditions control the decomposition rate and the mean residence time of the organic inputs. Here, B+LD showed the highest potential to storage C in a sandy soil, however its decomposition rate increased during the freeze-thaw events, reducing its persistence in the soil.

5 Conclusions

The MERMOLD project investigated whether a single application of organic materials and use of cover crops after the harvest of the early potato may improve soil conditions and increase SOM storage, and their effects on tuber yield and marketable potatoes. Our results show that one single application of OM increased the level of SOC stocks compared to the Control (no OM), while the presence of CC had a smaller effect. In the short-term, FYM and B+LD showed similar and higher potential to increase SOC stocks than the SD. SOM accumulation in the B+LD and FYM treatments occurred only in the particulate organic matter (POM) fraction. POM is not physically protected and decomposes quicker than that organic matter associated with soil minerals (mineral-associated organic matter; MAOM). In the laboratory incubation study, CO_2 emissions were used to estimate the decomposition rate and mean residence time of the organic materials in the experimental soil. Here, we observed a higher decomposition rate in the treatments with SD than those with FYM and B+LD, suggesting again a higher SOC storage potential for B+LD and FYM than SD. Within 100-day of incubation, SD treatments emitted 44-54% of the added C. The differences between the decay rates suggested that the application of B+LD has a higher persistence into a sandy soil compared to FYM and SD. Yet, during the freeze-thaw events the decomposition of the B+LD may increase, lowering its residence time in the soil.

The presence of CC significantly increased potato yield in 2021 and reduced the severity of potato diseases by 10% in the post-harvest potatoes in 2020 and 2021, while the yield of marketable potatoes after storage in 2021 was increased by 37% in the treatments with CC. The type of organic material did not affect significantly on potato yield or quality, but the proportion of marketable potatoes tended to be higher in the treatments where organic inputs were applied than in the Control. In our field experiment, we used only one early potato variety, Solist, however our results may have implications to other early potato varieties and storage potato varieties, as we observed a much stronger positive effect of CC on the severity of the diseases of the potatoes during storage.

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