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Novel carbon capture-based organo-mineral fertilisers show comparable yields and impacts on soil health to mineral fertiliser across two cereal crop field trials in Eastern England

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ABSTRACT

Context: Whilst mineral fertiliser is required to meet nearly 50% of global crop demand, its production is energy intensive and contributes close to 2% of the global emissions of greenhouse gases.
Objective: The aim of this study is to evaluate the efficacy of a novel fertiliser to meet crop demand and its impacts on soil health. This novel fertiliser incorporates point source carbon dioxide captured into organic matter balanced with mineral fertiliser. It is hypothesised that this carbon capture-based organo-mineral fertiliser (CCOMF) will mineralise and release nutrients adequate to meet demand of cereal crops.
Methods: Two field trials were conducted to evaluate the performance of CCOMF on winter wheat and winter barley. Each field trial compared three concentrations of CCOMF (5% N, 10% N, and 15% N) to a conventional mineral fertiliser treatment and an unfertilised control. Each fertiliser treatment was applied at the recommended application rate for the crops (270 kg/ha N and 180 kg/ha N, for winter wheat and winter barley, respectively). Each field trial included three additional application rates for each fertiliser treatment of 50% less, 50% more, and double the recommended rate in order to obtain a yield response curve. This totalled 160 experimental plots (2 field sites, 5 fertiliser treatments, 4 doses, with 4 replicates). All treatments were organised into a randomised block design with 4 replicates in both sites. The impact of the fertilisers on yield, soil nutrients, and root development were established by comparing baseline soil analysis and root measurements taken before the first application of fertiliser to samples taken at harvest.
Results: The results showed that the CCOMFs produced winter wheat and winter barley yields (7.49 ± 0.74 t/ha and 5.85 ± 0.29 t/ha, respectively for the 10% N) comparable to those produced following mineral fertilisers (7.40 ± 0.50 t/ha and 5.35 ± 0.16 t/ha, respectively). There was no significant fertiliser impact on soil organic carbon, microbial biomass, or pH. In terms of nutrients, there was also no significant difference in residual concentrations. There was also no significant difference in root development between the treatments.
Conclusion: This study showed that CCOMFs are a promising alternative to conventional mineral fertilisers as they produce comparable yields with no additional negative impacts in the short term.
Implications: This study is the first of its kind in a field context showing feasibility of using carbon capture technology to formulate sustainable fertilisers adopting a circular economy approach.

1. Introduction

Approximately 95% of the world's food production relies on fertile soil (FAO, 2015) however with the majority of the world's agricultural soils being classed as fair, poor, or very poor (FAO and ITPS, 2015) food production relies heavily on mineral fertiliser. Currently, 30% of farms in the UK relying solely on mineral fertilisers and upwards of 79% of cereal crops receiving at least one application of mineral nitrogen (N) fertilisers (DEFRA, 2021a). The production of N based mineral fertilisers are incredibly energy intensive and causes close to 2% of global greenhouse gas emissions (Menegat et al., 2022). Further to this, natural gas is one of the main components in N fertiliser production and therefore the volatility of natural gas supply directly impacts the cost having knock on effects on food costs. The rapidly increasing population and concurrent food demand escalation as well as the volatile fertiliser prices is putting increasing pressure on agricultural practices to continually maximise

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yield. Although modern agricultural practices have, thus far, been able to keep up with the growing demand for food, crop yields are beginning to plateau (Dhakal and Lange, 2021). Thus, there is a need for novel and innovative solutions that reduce the reliance on fossil fuels whilst continuing to maintain or indeed increase crop yield.

Global soil degradation further constrains food production (Rickson et al., 2015) with mineral fertiliser often regarded as both the solution and cause with associated impacts on soil acidification (Chien et al., 2008; Goulding, 2016; Peryea and Burrows, 1999; Wallace, 1994), reduced soil organic matter content (Lima et al., 2009), and restricting soil microbial communities (Chen et al., 2020). Soil degradation is a self-exacerbating negative spiral and is expected to accelerate (Borrelli et al., 2020; Trenberth, 2011). Whilst soil carbon stocks form part of organic matter, its decomposition can release carbon dioxide (CO_2) and methane (CH_4). These gases are catalysts for climate change and as the climate warms, soil decomposition is predicted to increase, creating a negative feedback loop (Davidson and Janssens, 2006). Agricultural soils have relatively little carbon stocks in comparison to peatland and permafrost soils so their ability to negatively influence the climate is limited. However, as agricultural soils and other degraded soils are estimated to have the capacity to sequester 50–66% of the 42–78 Gt of historic carbon loss (Lal, 2004), they do represent a large potential for carbon storage.

The practice of increasing soil organic matter has been heralded as a key method for carbon sequestration and soil remediation by policy makers (DEFRA, 2023) and academia (Cotrufo et al., 2019; Lal, 2004; Six et al., 2002). However, current arable intensive agricultural practices do not offer adequate capacity for the reintroduction of organic matter into the soil. Organic amendments, such as manures, anaerobic digestate, biosolids, and compost, are currently being utilised however, their poor nutrient balance and high water contents make them uneconomical to transport (Antille et al., 2013; Zebarth et al., 2011). As such, these organic amendments are often spread locally to source, in regions with high concentrations of livestock. Over use of any fertiliser can lead to nutrient build up in the soil which has negative environmental impacts (Gendebien et al., 2010; Zebarth et al., 2011).

With the price of mineral fertilisers continuing to fluctuate and the state of soil health decreasing, innovative solutions are needed to meet crop nutrient demands and ensure that sufficient organic matter is reintroduced into the soil. A form of organo-mineral fertiliser (OMF) is being explored as one such solution. OMFs are a relatively new concept that take organic waste products such as food waste, digestate, and farmyard waste and combines them with mineral fertilisers to produce a more desirable and balanced nutrient content. The mixture is dried and pelleted to make it easily storable and transportable. As such, this method of recycling organic waste promotes a circular economy and provides a balanced nutrients to meet crop demand whilst acting as a tool for the re-introduction of organic matter into agricultural soils. The novelty of the OMFs used in this experiment (Fig. 1) is that it incorporates captured carbon dioxide from a point source into organic waste material as further detailed in Lake et al. (2019).

The aim of this work was to evaluate the efficacy of this carbon capture-based organo-mineral fertiliser (CCOMF) to meet crop demand and its potential impact on soil heath and carbon sequestration in two cereal field trials in South-Eastern England.

2. Materials and methods

2.1. Experimental site

The experiment was conducted from 2020 to 2021 at Luton Hoo Estate, Luton, Bedfordshire, South-East, England on two fields, Common Hart (51° 50 ’ 13’’ N, 0° 23 ’ 40’’ W) and Foxfield (51° 50 ’ 1’’ N, 0° 23 ’ 11’’ W). Common Hart (CH) and Foxfield (FF) were sown with winter barley and winter wheat, on 14th September and 12th October 2020, respectively. These field sites had a minimum and maximum temperature of 4 °C and 17 °C, respectively and rainfall between 30 and 50 mm. Daylight ranged from 8 to 17 h. The previous crop was spring barley and oil seed rape for CH and FF, respectively. CH is considered to be a silty clay loam (16% sand, 54% silt, and 30% clay) and FF is considered a clay soil (12% sand, 43% silt, and 45% clay). Other soil properties are detailed in Table 1.

Fig. 1. Carbon capture-based organo-mineral fertilizer.

2.2. Experimental design

This experiment involved three mixtures of CCOMFs (Table 2) with 5% N (5 N), 10% N (10 N) and 15% N (15 N). The feedstock for these fertilisers was animal manure and crop residue based digestate and the mineral component was ammonium nitrate. The CCOMFs were compared to an unfertilised control (0% N) and the recommended mineral fertiliser treatment for their respective crops, which were ammonium nitrate (34.5% N) and a compound nitrogen and sulphur fertiliser (24% N, 6% S). Each fertiliser was applied at a recommended rate of 180 kg/ha N and 270 kg/ha N for winter barley (CH) and winter wheat (FF), respectively.

All fertiliser treatments were applied at the recommended N rate for the respective crops (Table 3). In order to obtain a crop yield curve, three additional treatments were considered for each fertiliser treatment, 50%, 150%, and double (200%) the recommended N. Each field

Table 1
Soil properties for both field sites.

	Common Hart		Foxfield	
	Average	StErr	Average	StErr
Total Nitrogen (%)	0.253	0.002	0.229	0.004
Total Phosphorus (mg/kg)	1117.4	16.6	942.0	13.9
Available Nitrogen (mg/kg)	11.66	0.97	13.22	0.76
Available Phosphorus (mg/kg)	66.53	1.12	37.71	0.81
Available Potassium (mg/kg)	249.0	6.5	229.9	4.2
Available Magnesium (mg/kg)	60.18	1.12	62.29	1.25
Organic Matter (%)	4.57	0.03	4.41	0.05
Total Carbon (%)	2.81	0.03	4.74	0.17
Carbon:Nitrogen	11.11	0.05	21.91	1.21
Total Organic Carbon (%)	2.60	0.06	2.16	0.10
Biomass carbon (ug/g)	352.4	7.4	423.3	8.1
Total Hydrogen (%)	0.982	0.011	1.113	0.022
pH	8.11	0.01	8.33	0.01
Texture	Silty clay loam		Clay	
Particle size distribution (%)	16% sand, 54% silt, and 30% clay		12% sand, 43% silt, and 45% clay	
Total Organic Carbon:clay ratio	0.087		0.048	

Table 2
Nutrient content of fertilisers. The Organo-mineral fertilisers are designated by their respective N content. There were two mineral fertilisers used in the mineral fertiliser treatment and these are designated MF1 = ammonium nitrate and MF2 = compound nitrogen and sulphur fertilizer.

	Organo-mineral fertiliser			Mineral fertiliser	
	5 N	10 N	15 N	MF1	MF2
Total Nitrogen (% w/w)	4.56	11.1	14.2	34.5	24
Available Nitrogen (% w/w)*	2.14	9.68	12.41	34.5	24
Total P_2O_5 (% w/w)	3.53	2.5	2.29		
Total K_2O (% w/w)	4.36	3.1	2.7		
Total SO_3 (% w/w)	1.25	2.25	4.22		15
Total Carbon (% w/w)	31.7	20.8	16.7		
Total Na_2O (% w/w)	1.36	0.85	0.73		
Total MgO (% w/w)	0.86	1.23	2.09		
Total CaO (% w/w)	4.48	8.44	1.41		
pH	7.4	7.4	6.6		
Moisture Content (% w/w)	18.6	10.8	17.8		
Total Copper (mg/kg)	62.4	39.3	36.1		
Total Zinc (mg/kg)	281	202	225		
Total Iron (mg/kg)	3444	2182	2350		
Chloride (% w/w)	1.82	1.34	1.27		
Total Cadmium (mg/kg)	0.3	0.2	0.1		
Total Aluminium (mg/kg)	1055	654	528		

* Available Nitrogen is calculated as the sum of nitric and ammoniacal nitrogen

site was set up in a randomized block design with 4 replicates of each treatment equalling 80 experimental plots per field and 160 in total (2 field sites, 5 fertilisers treatments, 4 doses, with 4 replicates). The plots measured 6 m x 2 m. Each plot had a 0.5 m boarder between them to facilitate sampling and limit cross-contamination. Fertilisers were applied by hand in 4 applications for winter wheat and 3 applications for barley (Table 3).

2.3. Soil and grain sampling

Soil samples were taken at the same main stages: baseline and at harvest, for both fields. A Dutch auger was used to take three cores from each plot to a depth of 20 cm. A full suite of analysis (Appendix 1) was conducted on the baseline and harvest samples collected from the plots that received the recommended dose of fertiliser and selected analysis was carried out on the treatments receiving differing doses of fertiliser. Winter barley was harvested on 22nd July 2021 and the winter wheat was harvested on 26th August 2021. The total grain from each plot was harvested by a Haldrup C-85 Plot Combine harvester with a 2 m cutter bar. The whole of each plot was combined but the exact length was recorded by hand to correct the yield calculation (t/ha) for any inaccuracies in the combined area. The total harvested grain was weighed by the combine and a subsample taken to analyse the moisture content.

2.4. Root scanning

To monitor the development of roots, a 105 cm minirhizotron (6.35 cm inside diameter, 7 cm outside diameter) compatible with the CI-600 In-Situ Root Imager (CID Bioscience, Inc. Ca–as, WA - USA), was inserted into each of the plots that received the recommended dose of N and control plots. First, a hole was dug using a mechanical auger at a ~45° angle and then the minirhizotrons were inserted. The aim was to bury the minirhizotron up to 80 cm however, due to the substantial number of rocks in the soil, the depth varied between 50 and80 cm. Scanned images of the roots were captured at two stages in the experiment: before the first application of fertiliser (baseline) and before the harvest (harvest). Images were produced at 600 DPI which is the highest resolution recommended by the supplier. Each image captures 21.6 cm of the minirhizotron so multiple images were taken to capture the entire length of the buried section. The resulting images were then spliced together and analysed using RootSnap! (Version 1.3.2.25; CID Bioscience, Inc. Ca–as, WA - USA). To account for any variation in depth of the tube, results are displayed in root length density, showing the length of root per area of the scanned images.

2.5. Statistical analysis

Treatment differences were first established based on the optimum dose comparing the fertiliser treatments impact on grain yield, root development, and residual soil propertied (organic matter, microbial biomass, pH, available N, available P, available K, Total P). The normality of the data was checked, and no transformation was needed for standard parametric tests though 3 outliers needed to be removed from the root development data. For yield, two-way ANOVA (anonan function in MATLAB) was used to establish if the yield differed between the two crops and if there was a fertiliser treatment effect on the yield. For the other soil and root properties repeated measures ANOVA (SPSS) was used for the same purpose but to also include a baseline and harvest measurements as one set of within subject factors and each fertiliser treatment and another set of within subject factors. For all properties that showed a significant impact of crop type, the data from the two experimental fields were then analysed separately with one-way ANOVA (anova1 function in MATLAB) and subsequent significant results were further analysed with a post-hoc pairwise comparison test (multicompare function in MATLAB) to established which treatments significantly varied. For the properties that did not show a significant crop type effect, the treatments from the two experimental fields were combined. Next, analysis of covariance (aoctool function in MATLAB) assessed whether the different doses of fertilisers had a significant impact on the measured property. Analysis of covariance was not conducted on root development, microbial biomass, or total P because, due to the time required for these procedures, only samples for the optimum dose was collected for these properties.

Table 3
Fertiliser application dates for each field and the quantity of N and corresponding fertiliser weights applied. The Organo-mineral fertilisers are designated by their respective N content. There were two mineral fertilisers used in the mineral fertiliser treatment and these are designated MF1 = ammonium nitrate and MF2 = compound nitrogen and sulphur fertiliser.

Field	Crop	Application	Date of Application	kg/ha of N applied	Weight of fertiliser applied (kg/ha)				
					5 N	10 N	15 N	MF1	MF2
Common Hart	Winter Barley	1st	11/03/2020	60	1200	600	400	174	
		2nd	23/03/2020	80	1600	800	533		333
		3rd	08/04/2020	40	800	400	267	116	
		Total		180	3600	1800	1200	290	333
Foxfield	Winter Wheat	1st	11/03/2020	60	1200	600	400	174	
		2nd	30/03/2020	80	1600	800	533		333
		3rd	16/04/2020	85	1700	850	567	246	
		4th	07/05/2020	45	900	450	300	130	
		Total		270	5400	2700	1800	551	333

3. Results

3.1. Yield

Two-way ANOVA revealed that yield was significantly influenced by both crop ($p < 0.001$) and treatment ($p < 0.001$). The winter wheat plots receiving fertiliser resulted in a higher yield (7.1 t/ha) in comparison to winter barley (5.5 t/ha; Fig. 2). One-way ANOVA of each crop yields revealed that for both winter barley ($p < 0.001$) and winter wheat ($p < 0.01$) all fertilised treatments produced significantly higher yield than their respective unfertilised control. For winter barley, 10 N produced the highest yield (5.85 ± 0.29 t/ha) followed by 15 N (5.74 ± 0.27 t/ha), mineral fertiliser (5.35 ± 0.16 t/ha), and lastly 5 N (5.04 ± 0.33 t/ha). Similarly, 10 N produced the highest yield in winter wheat (7.49 ± 0.74 t/ha), followed closely by the mineral fertiliser (7.40 ± 0.50 t/ha), 15 N (7.17 ± 0.79 t/ha), and 5 N produced the least yield (6.46 ± 0.53 t/ha). Though there were some consistent trends between crops, none of the differences between fertilisers were statistically significant.

Analysis of co-variance showed that, for both crops there was a significant relationship between increasing doses of fertiliser and yield ($p < 0.001$). However, only with winter barley (Fig. 3A) did the rate of increase differ between the fertilisers ($p < 0.05$), with 5 N producing much less yield at half dose but then increasing to highest yield when an extra 50% was applied to then reach a plateau. The other fertilisers showed an increase in yield up to the optimum dose, followed by a decrease when 150% was added. At double the optimum application dose the yield either decreased further with (10 N) or produced a similar rate of increase as seen between the half dose and the optimum dose (15 N and 34.5 N). For winter wheat (Fig. 3B), there was no significant difference in the rate at which increasing fertiliser dose increased yield, each fertiliser increased yield between the 50% dose and the 150% dose, except for the mineral fertiliser which saw a decrease in yield from the optimum dose to the 150% dose. Additionally, unlike 5 N which continued to increase yield with each dose, 10 N and 15 N saw a drop off in yield after the 150% dose.

3.2. Root development

For winter barley, the data was heavily skewed by three outliers that were 6.7, 6.2, and 3.3 folds greater than the average of their respective treatment (2.1 m/m^2, 1.1 m/m^2, and 3.3 m/m^2 for 10 N, 5 N, and mineral fertiliser, respectively). With these outliers removed, repeated measures ANOVA shows that root length significantly increased from baseline to harvest (Fig. 4) for both crops ($p < 0.001$) and there was also a significant difference between crops ($p < 0.05$) with winter wheat producing significantly greater root density than winter barley. One-way ANOVA shows that although there was no significant treatment effect for the winter barley ($p = 0.30$) or winter wheat ($p = 0.86$) crops, they both responded similarly to their respective fertiliser treatments. For winter barley, the amount of stimulated root growth increased with the concentration of N in the fertiliser, with 5 N showing the least (1.1 ± 0.6 m/m^2) followed by 10 N (2.1 ± 0.6 m/m^2), 15 N (3.1 ± 0.9 m/m^2), and mineral fertiliser (3.3 ± 1.0 m/m^2) however, there was a trend of the control (1.8 ± 0.7 m/m^2) to outperform the 5 N. For winter wheat, root development coincided with the concentration of N in the fertiliser with the 5 N again stimulating the least root growth (3.1 ± 1.1 m/m^2) followed by the 10 N (3.3 ± 1.1 m/m^2), 15 N (4.2 ± 0.8 m/m^2), and mineral fertiliser (4.4 ± 0.4 m/m^2). Though, for winter wheat the control (4.03 ± 1.5 m/m^2) outperformed both the 5 N and 10 N OMF.

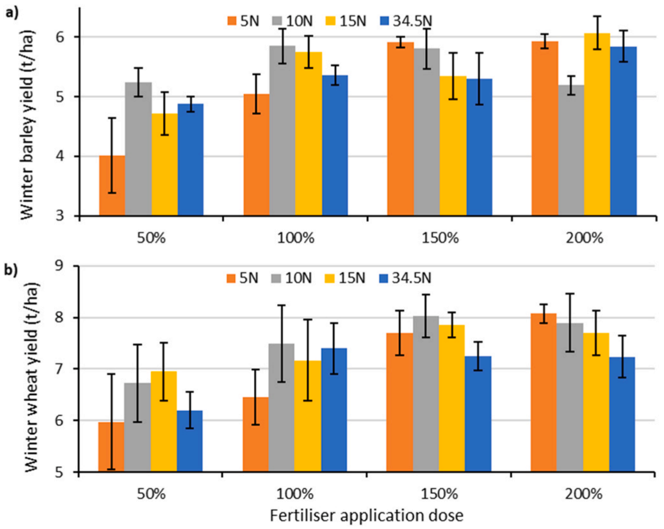

Fig. 3. Winter barley (a) and winter wheat (b) yield trends following application of different doses of organo-mineral fertiliser (5 N, 10 N, and 15 N) and mineral fertiliser (34.5 N). Error bars are equal to 1 standard error.

3.3. Soil organic matter

Through repeated measures ANOVA, each treatment showed a

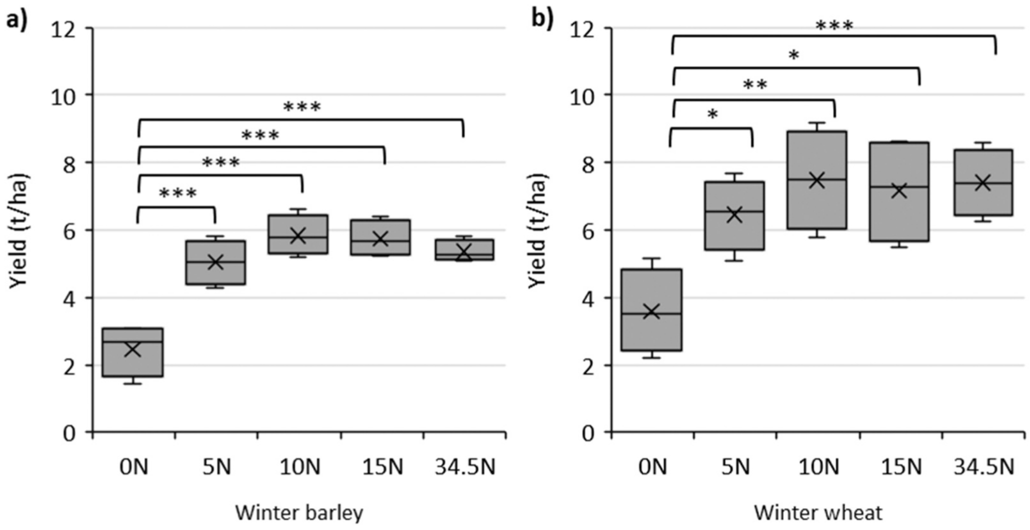

Fig. 2. Winter barley (a) and winter wheat (b) yields of the plots fertilised with organo-mineral fertiliser (5 N, 10 N, and 15 N) mineral fertiliser (34.5 N), and unfertilised control (0 N). The box represents the 1st and 3rd quartile with the median being the middle line and the whiskers show the range. The means of each treatment per crop type (represented by the X) were assess using a one-way ANOVA and significant is denoted as follows: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

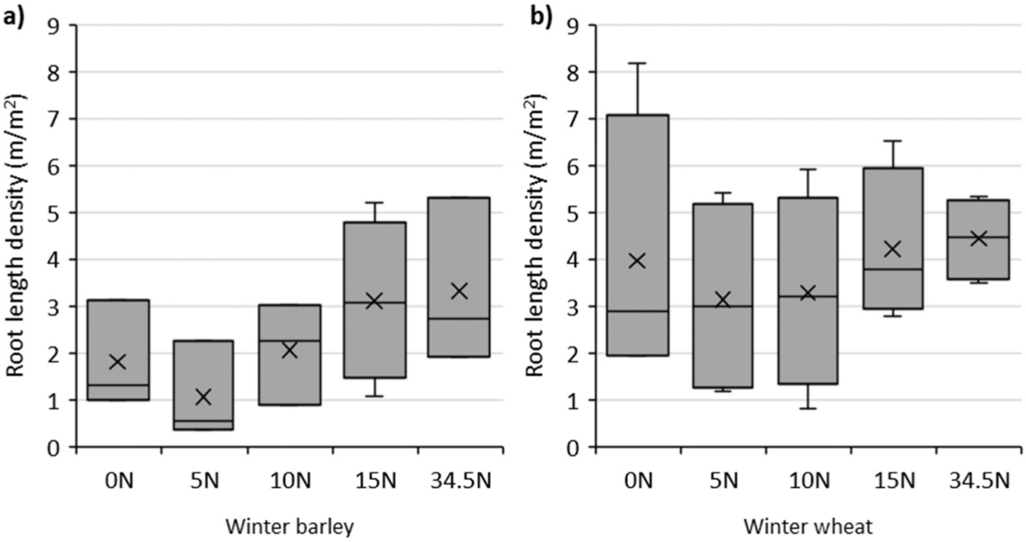

Fig. 4. Difference in root growth from baseline to harvest for the winter barley (a) and winter wheat (b) plots fertilised with organo-mineral fertiliser (5 N, 10 N, and 15 N) mineral fertiliser (34.5 N), and unfertilised control (0 N). The box represents the 1st and 3rd quartile with the median being the middle line and the whiskers show the range. The means of each treatment per crop type (represented by the X) were assess using a one-way ANOVA no significant differences were found.

significant ($p < 0.001$) increase in soil organic matter from the baseline by a mean of 2.22 ± 0.10% and 2.18 ± 0.19% for winter barley and winter wheat, respectively (Fig. 5) but there was no significant difference between the organic matter increase of each crop type ($p = 0.059$). The total amount of C added to each plot equated to 1.4 kg, 0.4 kg, and 0.2 kg of C per plot, respectively for 5 N, 10 N, and 15 N for the winter barley and 2.1 kg, 0.7 kg, and 0.4 kg of C per plot, respectively for 5 N, 10 N, and 15 N for the winter wheat. Despite this, one-way ANOVA reveals that there was no consistent or significant impact of treatment on the increase in organic matter content for winter barley or winter wheat ($p = 0.99$). For winter barley, the control treatment saw the largest mean increase in organic matter (2.54 ± 0.33) closely followed by 5 N (2.29 ± 0.24), mineral fertiliser (2.10 ± 0.21), 10 N (2.08 ± 0.09), and lastly 15 N (2.07 ± 0.13). For winter wheat 15 N saw the biggest increase in organic matter (2.68 ± 0.75) followed by 10 N (2.30 ± 0.40), control (2.24 ± 0.23), mineral fertiliser (2.08 ± 0.35), and lastly 5 N (1.60 ± 0.27). Further, analysis of co-variance showed that increasing dose of fertiliser did not impact the increase in soil organic matter content for either winter barley ($p = 0.95$) or winter wheat ($p = 0.78$).

3.4. Microbial biomass carbon

Repeated measures ANOVA showed that there was a significant change in the amount of microbial biomass (Fig. 6) from baseline to harvest for both crops ($p < 0.05$) and a significant crop response ($p < 0.001$). For winter barley, the amount of microbial biomass at harvest was significantly reduced in comparison to the baseline, resulting in a mean decrease of 12.96 ± 9.40%. Conversely, nearly all winter wheat plots saw an increase in microbial biomass from baseline to harvest by a mean of 38.79 ± 8.07%.

One-way ANOVAs showed that there was not a significant or consistent treatment effect on microbial biomass at harvest for either crop ($p = 0.40$ for winter barley, and $p = 0.65$ for winter wheat). For winter barley, the 5 N fertiliser showed the greatest mean microbial

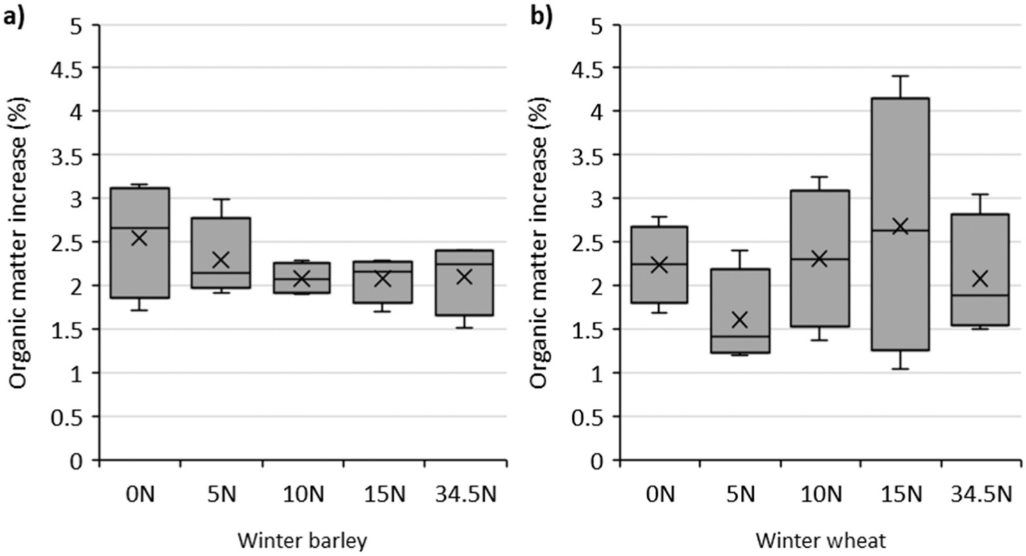

Fig. 5. Difference in soil organic matter content from baseline to harvest for the winter barley (a) and winter wheat (b) plots fertilised with organo-mineral fertiliser (5 N, 10 N, and 15 N) mineral fertiliser (34.5 N), and unfertilised control (0 N). The box represents the 1st and 3rd quartile with the median being the middle line and the whiskers show the range. The means of each treatment (represented by the X) were assess using a one-way ANOVA no significant differences were found.

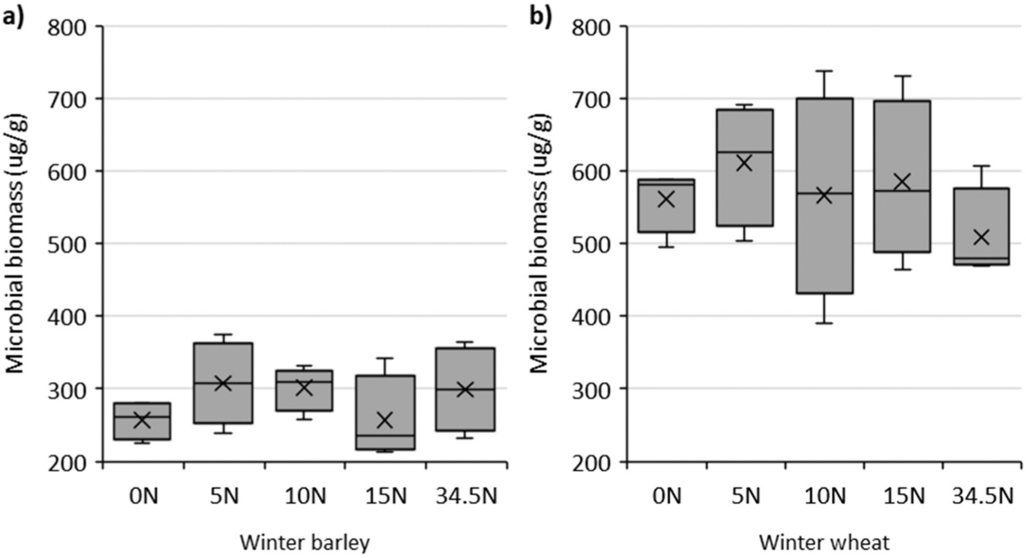

Fig. 6. Microbial biomass at harvest for the winter barley (a) and winter wheat (b) plots fertilised with organo-mineral fertiliser (5 N, 10 N, and 15 N) mineral fertiliser (34.5 N), and unfertilised control (0 N). The box represents the 1st and 3rd quartile with the median being the middle line and the whiskers show the range. The means of each treatment per crop type (represented by the X) were assess using a one-way ANOVA no significant differences were found.

biomass (307.5 ± 28.3 ug/g) followed by 10 N (301.2 ± 15.7), mineral fertiliser (299.0 ± 29.1), control (256.7 ± 14.0), and 15 N (256.5 ± 29.4). For winter wheat, 5 N again produced the greatest mean microbial biomass (611.1 ± 42.5) but followed by 15 N (585.2 ± 55.3), 10 N (566.1 ± 71.2), control (561.1 ± 22.2), and lastly mineral fertiliser (508.4 ± 33.0).

3.5. Soil pH

Soil pH significantly ($p < 0.001$) decreased for both crops between baseline and harvest (Fig. 7) but there was also a significant difference ($p < 0.001$) between the crop types as revealed by repeated measures ANOVA. pH in winter barley plots dropped by a mean of 8.10 ± 0.02–7.81 ± 0.04 whereas the pH of winter wheat was initially significantly higher (8.37 ± 0.02) and dropped to 8.26 ± 0.02. One-way ANOVA showed that there was little difference between the pH of each treatment for either winter barley ($p = 0.99$) or winter wheat ($p = 0.34$). For winter barley all three CCOMFs produced a soil pH of 7.83 (5 N, 7.83 ± 0.08; 10 N, 7.83 ± 0.06; and 15 N 7.83 ± 0.02) at harvest followed by the control (7.80 ± 0.14) and the mineral fertiliser (7.78 ± 0.10). For winter wheat, the control and 5 N treatments both produced the highest soil pH (8.30 ± 0.04) followed by 10 N (8.25 ± 0.06), mineral fertiliser (8.23 ± 0.09), and 15 N (8.22 ± 0.05). Likewise, analysis of covariance showed that there was no treatment effect brought on by differing doses of the fertiliser ($p = 0.33$ and $p = 0.89$ for winter barley and winter wheat, respectively). For winter barley increasing fertiliser dose did not significantly affect the soil pH however, for winter wheat the mean pH decreased with increasing dose ($p < 0.05$) for all treatments ($p = 0.55$).

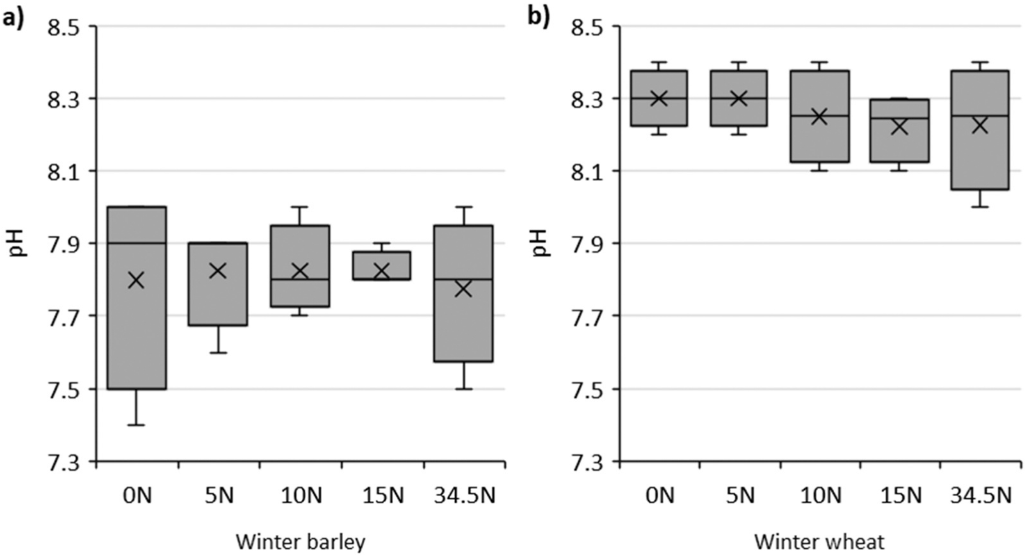

Fig. 7. pH at harvest for the winter barley (a) and winter wheat (b) plots fertilised with organo-mineral fertiliser (5 N, 10 N, and 15 N) mineral fertiliser (34.5 N), and unfertilised control (0 N). The box represents the 1st and 3rd quartile with the median being the middle line and the whiskers show the range. The means of each treatment per crop type (represented by the X) were assess using a one-way ANOVA no significant differences were found.

3.6. Available N

Repeated measures ANOVA showed that the amount of soil available N at harvest was neither significantly different to baseline ($p = 0.16$) nor between the two crops ($p = 0.09$). However, for winter barley the mean available N at harvest was greater than that of the baseline for all treatments except the control. For winter wheat there tended to be little change except for the control and the 10 N which saw a slight drop. Likewise, one-way ANOVA showed that there was no significant difference between the treatments for either crop ($p = 0.62$) though there were much higher fluctuations in the means of available N in winter barley than winter wheat showing that there was greater spatial variability in the winter barley plots (Fig. 8). When considering the results from the analysis of covariance, the available N of winter barley soil was not significantly impacted by increasing fertiliser dose ($p = 0.57$), however for winter wheat, increasing fertiliser dose did significant increase available N ($p < 0.001$) though the type of fertiliser did not influence this increase ($p = 0.50$).

3.7. Available P

Repeated measures ANOVA showed that there was significantly lower available P (Fig. 9) at harvest than there was at baseline ($p < 0.001$) and there was significantly ($p < 0.001$) more available P in winter barley (55.1 ± 2.1 mg/kg) than in winter wheat (36.7 ± 1.3 mg/kg). One-way ANOVA revealed that there was, however, no significant difference between treatments for either winter barley ($p = 0.51$) or winter wheat ($p = 0.42$). When considering analysis of covariance results, for winter barley, increasing fertiliser dose significantly increased the amount of available P ($p < 0.05$) however type of fertiliser did not affect this ($p = 0.56$). For winter wheat, there was not a consistent increase in available P with increasing dose of fertiliser however, 5 N proved to increase available P more than the other fertiliser when the full spectrum of doses was considered ($p < 0.001$), suggesting that although the optimum dose did not produce a significant increase, providing more than recommended would significantly increase available P over the other fertilisers.

3.8. Available K

Repeated measures ANOVA showed that the amount of available K was significantly ($p < 0.001$) higher at the baseline than at harvest though the reduction was significantly ($p < 0.001$) greater for winter barley than for winter wheat (from 237.3 ± 11.0 mg/kg to 118.4 ± 6.9 mg/kg, and from 222.1 ± 7.2 mg/kg to 203.8 ± 9.3 mg/kg, respectively). Again, one-way ANOVA showed that there was no consistent or significant difference between the treatments (Fig. 10). For winter barley the control treatment had the greatest residual available K (139.6 ± 22.5 mg/kg) followed by 5 N (132.1 ± 14.8), 15 N (116.1 ± 15.7), and mineral fertiliser (103.6 ± 8.0) closely followed 10 N (100.8 ± 9.9). For winter wheat, 5 N (247.3 ± 29.0), 10 N (214.6 ± 19.5), 15 N (197.9 ± 12.6), control (190.9 ± 9.6), and lastly the mineral fertiliser (168.4 ± 10.2). Although there was no consistency in the treatment order, the 5 N was amongst the highest values for available K, and the mineral fertiliser was amongst the lowest values. These trends are exaggerated when considering the difference doses with analysis of covariance. For both winter barley ($p < 0.01$) and winter wheat ($p < 0.001$), 5 N consistently produced significantly greater residual available K than the other treatments and in winter wheat increasing doses of 5 N increased residual available K at a greater rate than the other fertilisers ($p < 0.01$). Additionally, the mineral fertiliser consistently saw the lowest mean values of available K at harvest than the other fertiliser in winter wheat, however, was comparable to the 10 N and 15 N in winter barley.

3.9. Total P

Total P changed significantly ($p < 0.05$) from baseline to harvest when considering the results of repeated measures ANOVA, there was also a significant interaction ($p < 0.001$) between crop type and sampling period this is because for winter barley there was a trend for total P to decrease from baseline to harvest (1117.4 ± 11.3 mg/kg to 1052.4 ± 16.6 mg/kg) whereas for winter barley it increased (from 942.0 ± 15.3 mg/kg to 976.0 ± 16.6 mg/kg). One-way ANOVA showed that there was no significant ($p = 0.577$ and $p = 0.172$ for winter barley and winter wheat, respectively) or consistent difference between the treatments for either crop (Fig. 11). For winter barley, 5 N had the highest values (1107.8 ± 20.8 mg/kg), followed by the mineral fertiliser (1088.8 ± 41.3 mg/kg), 10 N (1053.3 ± 42.9 mg/kg), control (1016.5 ± 23.5 mg/kg), and lastly 15 N (995.8 ± 41.1 mg/kg). For winter wheat 10 N had the highest value (1049.8 ± 37.0 mg/kg) followed by 15 N (984.5 ± 22.8 mg/kg), mineral fertiliser (974.5 ± 25.1 mg/kg),

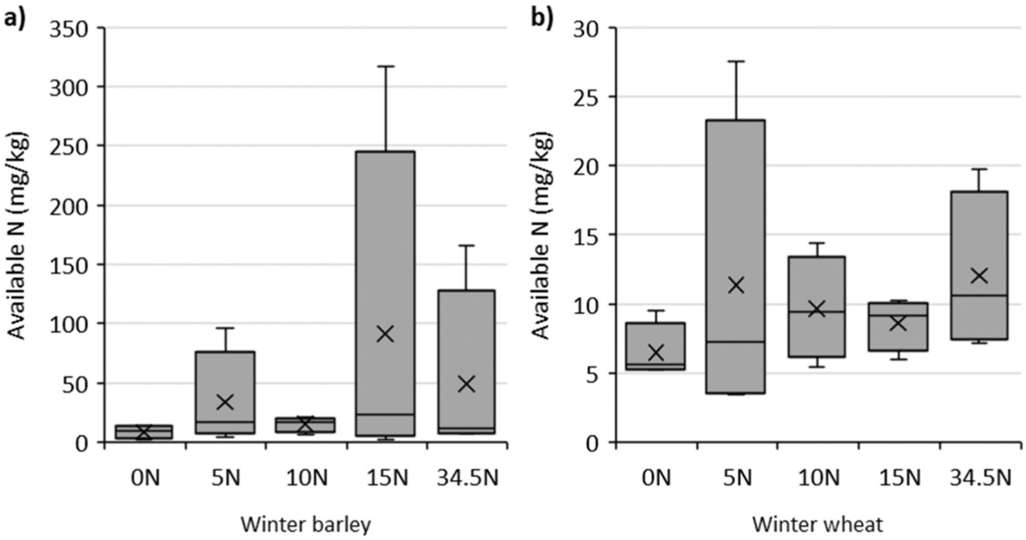

Fig. 8. Available N at harvest for the winter barley (a) and winter wheat (b) plots fertilised with organo-mineral fertiliser (5 N, 10 N, and 15 N) mineral fertiliser (34.5 N), and unfertilised control (0 N). The box represents the 1st and 3rd quartile with the median being the middle line and the whiskers show the range. The means of each treatment (represented by the X) were assess using a one-way ANOVA no significant differences were found.

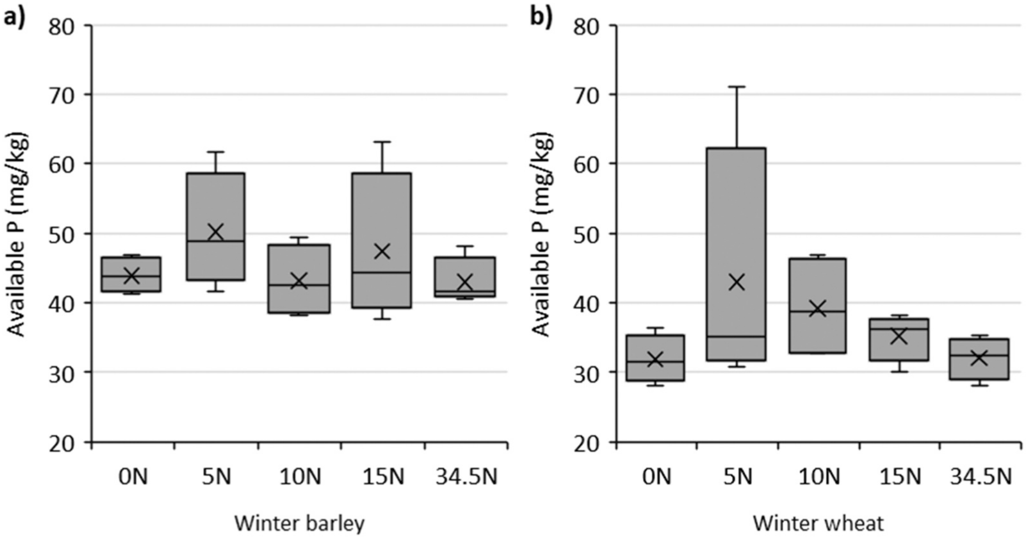

Fig. 9. Available P at harvest for the winter barley (a) and winter wheat (b) plots fertilised with organo-mineral fertiliser (5 N, 10 N, and 15 N) mineral fertiliser (34.5 N), and unfertilised control (0 N). The box represents the 1st and 3rd quartile with the median being the middle line and the whiskers show the range. The means of each treatment per crop type (represented by the X) were assess using a one-way ANOVA no significant differences were found.

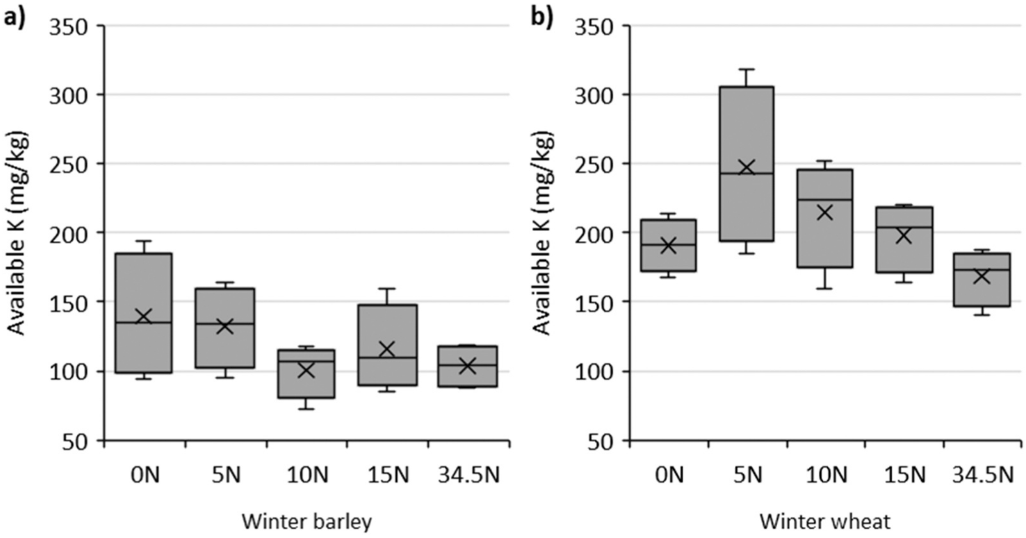

Fig. 10. Available K at harvest for the winter barley (a) and winter wheat (b) plots fertilised with organo-mineral fertiliser (5 N, 10 N, and 15 N) mineral fertiliser (34.5 N), and unfertilised control (0 N). The box represents the 1st and 3rd quartile with the median being the middle line and the whiskers show the range. The means of each treatment per crop type (represented by the X) were assess using a one-way ANOVA no significant differences were found.

5 N (956.8 ± 42.5 mg/kg), and lastly the control (914.3 ± 27.5 mg/kg).

3.10. Metals

All metals, except for nickel, showed a significant difference from baseline to harvest (Appendix 2). Copper, zinc, cadmium, and manganese also showed a significant interaction between sampling period and crop. Copper and manganese decreased in winter barley but increase in winter wheat. For Zinc winter barley saw a much higher baseline than winter wheat but also saw a much larger increase. Cadmium again saw much higher baseline levels in winter barley, but winter wheat saw a much greater increase from baseline. The mineral fertiliser consistently saw the highest (or second higher) mean total metal for each metal and both crops. For winter wheat, metal content tended to increase with increasing %N from control to 5 N, 10 N, 15 N, and lastly mineral fertiliser. For winter barley, there was no correlation with N content, 15 N consistently produced the lowest metal content but there was no consistent order between the control, 5 N and 10 N.

4. Discussion

This study is the first of its kind to demonstrate field scale evidence on the efficacy of carbon capture-based organo-mineral fertilisers (CCOMF) to meet crop demands and their impact on soil properties. The field study, conducted in South-Eastern England, compared three formulations (5 N, 10 N and 15 N) of CCOMFs to a standard mineral fertiliser application (ammonium nitrate with added sulphur; Table 2). Each fertiliser was applied at the recommended N dose of 270 kg/ha N and 180 kg/ha N for winter wheat and winter barley, respectively and their relative impact on crop yield, root development, and various soil properties were analysed.

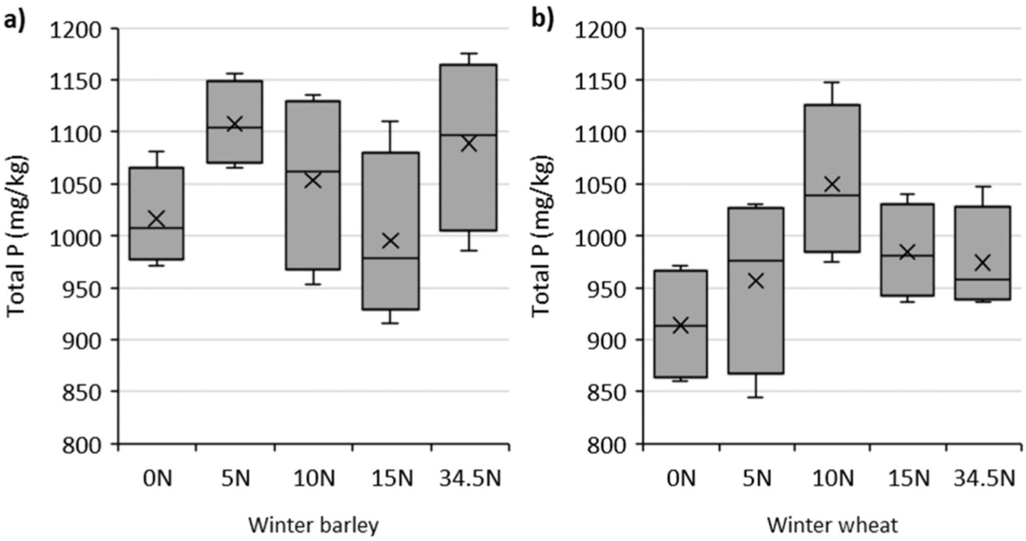

Fig. 11. Total P at harvest for the winter barley (a) and winter wheat (b) plots fertilised with organo-mineral fertiliser (5 N, 10 N, and 15 N) mineral fertiliser (34.5 N), and unfertilised control (0 N). The box represents the 1st and 3rd quartile with the median being the middle line and the whiskers show the range. The means of each treatment per crop type (represented by the X) were assess using a one-way ANOVA no significant differences were found.

4.1. Fertiliser impacts on crop yield

All fertiliser treatments (including the mineral treatments) for both crop types yielded lower than the UK average for 2021 (7.8 t/ha and 6.4 t/ha for wheat and barley respectively; DEFRA, 2021b). This is likely due to the plots being located in the headland of the field for both sites. Despite this, all CCOMFs produced comparable yields to the mineral fertiliser treatment (Fig. 2). These findings are mirrored in other studies that compare OMFs to mineral fertiliser treatments. Deeks et al. (2013) found that OMF produced similar yields to mineral fertilisers over three growth periods and across three different crops (Forage maize, Oilseed rape, Winter wheat, and Spring beans). Pawlett et al. (2015) and Antille et al. (2017) reported a similar observation to Deeks et al. (2013) but for grass and cereals, respectively. This suggests that the inclusion of carbon capture technology into the production of OMFs does not have any adverse effects on crop yield and that their nutrients can effectively meet crop demand in the first growth season of application.

There was no consistent trend in the results to suggest whether the ratio of organic N to mineral N in the CCOMFs (Table 2) had an impact on yield. Though the 15% N CCOMF (15 N) yielded higher than the 5%N CCOMF (5 N), it was the 10%N CCOMF (10 N) that produced the highest mean yield out of all the fertiliser treatments including the mineral fertiliser treatment. This may be explained by a disparity in N application. The application rates were calculated based on the CCOMFs advertised N content of 5%, 10%, and 15% N (Table 3), however, the N contents of the 5 N and 15 N were just under reported (4.56% and 14.2%, for the 5 N and 15 N, respectively) and the 10 N was just over at 11.1%. This discrepancy means that the 10 N plots received more N than the other treatments which likely explains why it produced the highest yields. However, this also means that two of the CCOMFS (5 N and 15 N) received a suboptimal application of N but still produced similar yield to the mineral fertiliser. It can then be concluded that not only are the nutrients plant available in the first season after application but that they are able to perform as well as mineral fertilisers in meeting crop demand.

When considering the efficacy of the fertilisers, it is important to note the physical properties of the pellets. With the 5 N and 10 N, which were made in batches of 1400 kg and 730 kg, respectively, the pellets held their shape well throughout the spreading season. The 15 N pellets, made in a batch of 370 kg, were much more friable than the other two. It is suspected that this difference is due to the batch quantity of the 15 N being outside the best operational range of the production equipment which are designed for dealing with larger quantities. Consequently, the 15 N pellets showed to be more brittle and cause more dust, this could have contributed to nutrient losses as the conditions were often quite windy during periods of application, preventing the crops from receiving the full nutrient application and produced diminished yields. Despite this the 15 N performed comparable to the other treatments so this would not have significantly impacted the results.

4.2. Fertiliser impact on soil parameters

Within this study, there were no detrimental effects on soil parameters such as organic matter, microbial biomass carbon, or pH due from the application of the CCOMFs. Conventional agricultural practices, at best, maintain an equilibrium of low soil organic matter in tilled crops, where the organic carbon sequestered by the roots and their exudates balance the annual breakdown of soil organic carbon (Loveland and Webb, 2003). Roots carbon rich exudates increase soil aggregation (Loveland and Webb, 2003) and actively feed and stimulate the growth of micro-organisms which will eventually add to stable carbon pools (Haichar et al., 2014) as do the roots themselves when they reach senescence (Lorenz and Lal, 2005). Likewise, various forms of organic matter contain physiologically active substances that promote root growth that are not present in inorganic fertilisers (Dobbss et al., 2007). In this study, there was no significant effect on root length measurements between either crops or fertiliser formulations suggesting that there was also no difference in the contribution of plant derived soil carbon. It is important to note that there were limitations to the method of root analysis used in this study. Due to the high rock content, root penetration was not uniform. This resulted in high variability in the data which was further exacerbated by varying depths of the tubes. However, other studies comparing the impact of digestate on root development to mineral fertilisers also reported either no difference in root development (Ren et al., 2020) or a decrease (Andruschkewitsch et al., 2013), suggesting that digestate, which was the organic feedstock for the CCOMFs used in this study, does not provide any additional benefits to root development. These results may also be a result of the distribution of nutrients. Root systems are heavily responsive to nutrient pools (Hodge, 2004) and their distribution can significantly impact root growth. Plants have been shown to produce more expansive root systems when the nutrient pools are heterogeneously distributed (Fransen et al., 1999; Li et al., 2016). The amount of fertiliser pellets applied would have been directly related to their N concentration with the higher concentration pellets being distributed relatively sparsely and the lower concentration fertilisers being more homogenously distributed. This may also explain why the 5 N and 10 N produced equivalent or less root growth than the control. As such, there are many variables that can determine root development and it is not clear which are the dominant mechanisms controlling root development in this study.

The inclusion of an organic feedstock into CCOMFs also makes them a potential source of soil carbon, with the 5 N incorporating greatest quantities at 1.4 kg C per plot in the winter barley and 2.1 kg C per plot in winter wheat. However, despite this there was no significant difference in the residual organic matter content of the treatments. Soil clay content affects SOC protection, including adsorption on mineral surfaces and within soil aggregates (Dungait et al., 2012). The SOC/clay ratio for the soils in this study were 0.087 and 0.048 for the winter barley and winter wheat, respectively and therefore classified as moderate and degraded, respectively (Prout et al., 2021). The C:N ratio of the CCOMFs are also low (ranging from 1.18 to 6.95; Table 2) which suggests the soil micro-organisms were not carbon limited (Spohn and Chodak, 2015) and that the introduced carbon from the CCOMFs would be easily utilised and respired by soil microbes. However, as there was also no difference in microbial biomass (Fig. 6), it can also be assumed that the increased carbon did not stimulate microbial activity. As such, the lack of organic matter build-up is expected considering that the build-up and utilisation of soil carbon can take much longer than the length of this study (Antil and Singh, 2007; Obriot et al., 2013). Organic matter needs intervention from soil organisms to be incorporated into the soil and until then it remains largely on the surface and spatially sporadic, therefore making build-ups difficult to capture. Extended periods of study are necessary to accurately gauge the impact of these CCOMFs on organic matter build-up.

With regards to residual nutrient content there was no significant or consistent increase in the nutrient content at harvest in comparison to that of the baseline for either treatment. The fertiliser application rates were determined by the N content of the fertilisers, so it is unsurprising that there was no significant difference between the treatments and the lack of build-up suggests that the applied N was mostly taken up by the plants unless it remained locked in the spatially sparse CCOMF pellets. This seems especially the case for the 10 N which showed the lowest increase in residual N but produced the highest yields. Due to their organic feedstock, treatments receiving the CCOMFs received doses of phosphate and potassium extra to that of the mineral fertiliser that only received the recommended applications of nitrogen and sulphur. This could have potentially led to a build-up of nutrients if they were not used up by the plants. However, for available P and K, there was a significant decrease from baseline to harvest suggesting again that all the applied nutrients were taken up by the plants. There was a trend that mineral fertiliser application created a greater decline when compared to CCOMFs in the clay soil (winter wheat) showing that repeat applications of CCOMF could increase soil fertility over mineral fertiliser treatments.

The levels of heavy metals such as Cd, Cu and Zn in the CCOMFs were within the maximum permissible levels according to the Code of Good Agricultural Practice (MAFF, 1998). The soil analysis post-harvest indicated no particular trend in build-up that goes more than stipulated legislative guidelines. However, this would need to be monitored in subsequent years if repeated applications of CCOMFs with anaerobic digestate feedstock are applied.

5. Conclusions

The novel organo-mineral fertilisers produced by combining point source CO_2 captured into organic waste material (CCOMF) offers promising results as a potential sustainable alternative to mineral fertilisers after one growing season. The application of CCOMFs did not have any significant detrimental impacts on yield resulting in winter wheat and winter barley yields that are comparable to mineral fertilisers. The mineral fertiliser treatment produced the greatest root growth though it is unsure whether this is a result of proportion of available nutrients or the relative heterogeneous distribution of the nutrients. In addition, there was no detrimental effect on soil parameters such as organic carbon, microbial biomass, and pH. The residual soil nutrient levels (available N, P and K) showed no significant increase from the baseline levels indicating that the supply coming from the applied fertilisers met the crop demands and did not result in any residual build-up. There were also no concerns raised over soil heavy metal contamination as soil heavy metal levels following all our treatments were within the legislative guidelines. Although longer-term trials are needed to fully monitor the impacts of these CCOMFs on soil health, this initial study offers early evidence that using carbon capture-based organo-mineral fertilisers can reduce the need for mineral fertilisers with no detrimental impacts to crop yield and or soil health after the first season of application.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data supporting this study are openly available from the CORD repository at DOI 10.17862/cranfield.rd.23676486.

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