TITLE: FIELD LEVEL VARIATION INFLUENCED OUTCOMES MORE THAN N-FERTILISER, FYM, COVER CROPS OR THEIR LEGACY EFFECTS FOLLOWING CONVERSION TO A NO-TILL ARABLE SYSTEM

AUTHORS: Ana I.M. Natalio[12], Matthew A. Back[1], Andrew Richards[3] and Simon Jeffery[1]

[1]Agriculture and Environment Department, Harper Adams University, Newport, TF10 8N, UK
[2]Division of Agricultural and Environmental Sciences, Sutton Bonington, LE12 5RD, UK
[3]Agrii, Andoversford, Cheltenham GL54 4LZ, UK
Correspondence to: Ana I.M. Natalio (ana.imnatalio@nottingham.ac.uk)

Twitter handles: @AnaNatalio ; @DrMattBack ; @Dr_S_Jeffery ; (Andrew not on twitter)

This draft is an update of the preprint published online on 04/08/2022
ID: 3491
Title: Field’s spatial variation influenced outcomes more so than N-fertiliser, FYM, cover crops or their legacy effects following conversion to a no-till arable system
DOI: 10.31223/X5SH2G

Title: Field level variation influenced outcomes more than N-fertiliser, FYM, cover crops or their legacy effects following conversion to a no-till arable system

Ana I.M. Natalio[1,2] Matthew A. Back[1], Andrew Richards[3] and Simon Jeffery[1]
[1]Agriculture and Environment Department, Harper Adams University, Newport, TF10 8N, UK
[2]Division of Agricultural and Environmental Sciences, University of Nottingham, Sutton Bonington, LE12 5RD, UK
[3]Agrii, Andoversford, Cheltenham GL54 4LZ, UK
Correspondence to: Ana I.M. Natalio (ana.imnatalio@nottingham.ac.uk)

1 Abstract

Crop establishment in no-till arable systems benefits from favourable soil conditions. Combined with the incorporation of crop residues and manures, no-till can influence soil organic carbon (SOC) and organic matter (SOM) dynamics, crop productivity and nutrient cycling. These processes are shaped by spatial and temporal factors and associated microbial processes. There is a lack of diachronic large-scale field studies that include baseline data and capture seasonal variations in arable systems. This study aimed to investigate the interaction between microbial and soil physicochemical properties as they evolved over time during the transition from full-inversion to no-till soil management. It utilised a combination of soil microbial assays (microbial biomass carbon (MBC) and nitrogen (MBN) with bio-physico-chemical analyses (SOC and SOM quantification, textural class, pH, gravimetric water content (GWC), and macronutrients) to assess soil over two years. Two experiments were established within the same four-hectare field: one on a relatively level area (Experiment-1) and another on a slope (Experiment-2). Experiment-1 treatments consisted of Farmyard Manure (FYM), Green Manure (GM) and Standard Practice (SP = Control). Experiment-2 was a repeat of Experiment-1, but without the FYM treatment. Soil was sampled twice per crop season, in Spring and Autumn, in Expriment-1, and in Autumn only in Experiment-2. The results were influenced by spatial and temporal variations that were not always linked to management practices. This two-year study demonstrated that the quantification of SOC and SOM were poor predictors of change in management practices over the timeframe of the study, but that microbial biomass responded quickly to the incorporation of FYM. SOC and SOM were affected by soil texture, but not significantly by inputs, and were associated with extractable Ca^{2+} and total-N. This study demonstrates that diachronic studies increase our understanding of SOC, SOM, MBC and MBN dynamics and the impacts of short-term change in soil management practices.

Furthermore, spatial variation within one field was found to lead to different outcomes and to be a better predictor of response to management.

2 Introduction

Soils are critical to life, playing a central role in agricultural systems and ecosystem service provision whilst being a habitat for a remarkable diversity and abundance of life (Orgiazzi et al., 2016). Soil is a dynamic environment, and its biological and physicochemical aspects infuse it with various degrees of functionality. Soil is commonly thought of as a “Black Box” because of the challenge in untangling interactions between the different functional components to understand the mechanisms behind processes (Denef et al., 2002; Six et al., 2004). This means that, historically, soil management was results based, with little concern of the underlying mechanisms or impacts if soil management interventions supported or enhanced yields.

Agricultural practices such as full inversion tillage, removal of crop residues and periods of fallow have been linked to the degradation of soils, threatening their productivity and sustainable use (Arneth et al., 2019; Evans et al., 2020). These practices have led to loss of SOM, and thus SOC, and biodiversity, caused soil erosion, impoverished soil structure and weakened water infiltration capacity (Rowley et al., 2018; COP21, 2015; Lal, 2016; Arneth et al., 2019; Evans et al., 2020). A change to agricultural practices which preserve soils and prevents further degradation is urgently required to ensure the sustainability of crop production (Lal, 1997; Tsiafouli et al., 2015; Science 20, 2018; Searchinger et al., 2019; Arnold et al., 2020). There has been increasing focus on identifying optimum management practices to reduce fertiliser inputs whilst improving soil health and produce economically viable yields (NFU, 2019; Searchinger et al., 2019; CCC, 2020).

Adoption of no-till (i.e. zero tillage with direct drilling) in arable systems, a cultivation that minimises soil disturbance, has been promoted as a practice in soil protection to increase soil organic matter and build carbon stocks (C), and prevent loss of structure, compaction, and nutrient leaching (Tsiafouli et al., 2015; Arneth et al., 2019; Searchinger et al., 2019; Arnold et al., 2020; Evans et al., 2020; No-Till.UK, 2020). It has been estimated that only 3-7% of the agricultural land in the UK is managed as no-till (Allison, 2015; Alskaf et al., 2020). Part of the reason for poor uptake is the yield penalties that are often reported during the first years of conversion (Pittelkow *et al.*, 2015).

Manures are frequently applied in arable systems, and interest in sowing cover crops has intensified, which are two approaches recommended for building soil health in addition to no-till (Roesch-Mcnally et al., 2018; Abdalla et al., 2019; Lin et al., 2019; Storr et al., 2019). Farmyard manures (FYMs) are applied on 51% of surveyed British farms, of which the greatest volume originates from beef and dairy farms (National Statistics, 2019). Cover cropping is also increasingly promoted as beneficial to soil and the environment through their preventive and/or restorative role against soil degradation (Roesch-Mcnally et al., 2018; Storr et al., 2019). These inputs can vary in their nutrient composition. For example, the N-content of manures can vary from 6 kg N t^{-1} to 30 kg N t^{-1} depending on whether they are from cattle or poultry (Defra, 2018). Cover crops also vary in their N-content and their C:N ratios influence the effects of soil priming that impact nutrient stoichiometry (Liu et al., 2020). For example, legume crops can typically have C:N ratios of 8 – 15 : 1, whereas cereal crop residues can be as high as 80:1 (Silgram and Harrison, 1998; USDA-NRCS, 2011; Schrumpf et al., 2013). Therefore, the characteristics of the soil amendment along with the inherent characteristics of soil is one main factor that controls nutrient dynamics.

No-till can reduce decomposition rates by approximately 10-20%, with functions such as of organic matter associated nutrient cycling being reduced too, although not halted completely (Lupwayi et al., 2004; Janzen, 2006). Moreover, temporal patterns influence microbial communities, and dynamic changes can be rapidly triggered through resource addition such as N-inputs. Microbial decomposition is further influenced by physicochemical properties of soil, such as texture, temperature, and water content (Schmidt et al., 2011; Kallenbach et al., 2016). It has been argued that these properties determine the persistence of SOC/SOM more so than the chemical properties of the inputs (Schmidt et al., 2011).

There is a disparity of results from studies investigating no-till, with some showing increased C stocks and others not. This disparity arises from the specifics of each experiment such as longevity of the experiment, crop diversity and frequency of crop rotation (Luo et al., 2010; Virto et al., 2012; Powlson et al., 2014; Valboa et al., 2015; Parthasarathi et al., 2016; Meurer et al., 2018). Moreover, considering farming is a business requiring profits to sustain it and reinvest, it is important to understand potential causes of yield penalties if they occur and soil macronutrients dynamics in no-till systems (Watts et al., 2006; Storr et al., 2019). Therefore, this study aimed to investigate impacts associated with the application of N-fertiliser alone, and in combination with FYM, and the sowing of cover crops for use as green manure, on SOC/SOM dynamics under no-till, considering microbial biomass as both derived by inputs and as a precursor of SOM/SOC, physicochemical properties and crop productivity in a large scale, two-crop-years field experiment. Both SOM and SOC have been measured because the former is usually more accessible to farmers, but it has been suggested the latter to be a better approach (Pribyl, 2010; Abram, 2020). Furthermore, applying a universal factor to convert organic carbon to organic matter is likely to under or overestimate it because measurements can be influenced by management and soil inherent properties (Pribyl, 2010). Thus, it was important to understand the response of both under the experimental conditions used and offer an additional case study for comparability. Two field experiments were established in the UK on arable land that was historically under a full inversion tillage. It was hypothesised that:

1. The effect of incorporating farmyard manure on SOC, SOM, and macronutrients is measurable over two-year period.
2. Cover crops will cause increase in microbial biomass, SOC and SOM.
3. The nutrient status of soil changes with the type of organic amendments.
4. Soil textural heterogeneity has a greater impact on soil properties than inputs.
5. Yield penalty presence is dependent on soil characteristics.

3. Materials and Methods

3.1 Experimental Design

The experiments were established at Norbury Park, Staffordshire, United Kingdom (52°48'20.9"N, 2°17'49.9"W). Textural class of the field varied from clay loam to sandy loam (Table 2). Experiment-1 consisted of three treatments: Farmyard Manure (FYM), Green Manure (GM) and Farmers' Standard Practice (SP = Control). Experiment-2 was conducted on a sloping side of a field and excluded the FYM treatment. Spring wheat (*Triticum aestivum* var. Mulika with Beret Gold seed dressing) was direct drilled on all plots except GM plots. Fodder radish (*Raphanus sativus*) and vetch (*Vicia sp*.) were also direct drilled, at a seed ratio of 50:50, as a green manure (GM) for the next crop season. The control plots were managed as per farmer standard practice (SP, i.e. using synthetic N at maximum rates permissible under RB209 (Defra, 2010)). Nitrogen fertiliser was applied too in the FYM plots to equalise total N inputs. The following crop season had winter oats (*Avena sativa* var. Mascani with Beret Gold seed dressing) which were direct drilled across all plots in both experiments. Refer to Table 1 for detailed field record.

3.2 Soil Sampling and Processing

Baseline soil sampling of Experiment-1 was conducted on 03/05/2017. Aboveground biomass sampling took place on 20/09/2017 for both experiments. Post-harvest soil sampling was done on 12/10/2017 for Experiment-1 and on 15/11/2017 for Experiment-2.

Subsequent crop season had spring sampling of Experiment-1 on 30/04/2018, and in autumn soil on 02/10/2018 of Experiment-1 and 01/11/2018 of Experiment-2.

3.2.1 Experiment-1

Sampling points were selected using a random number table (Rand Corporation, 1955) to determine how far down each plot to sample. Twenty soil cores were collected from each sampling point using an auger (10 cm depth * 4.5 cm diameter). Plots were sampled individually, at two sampling points, with one composite sample of 20 cores produced per sample point, and a total of 40 soil cores per plot. Sampling was conducted at least one meter away from plot boundaries at all points. Soil samples were kept in a press-grip plastic bag in a cooler box in a shaded area and subsequently in a fridge overnight at 4°C. Stones and plant residues were removed from soil before homogenising samples by sieving (4 mm mesh) and hand mixing fresh soil samples. Subsamples were prepared for microbial biomass and physicochemical analyses. All subsamples were kept refrigerated at 4°C until analysis with microbial assays performed within 10 days of sample collection (Wang et al., 2021).

3.2.2 Experiment-2

Each plot was sampled individually using the zig-zag sampling pattern (Krebs, 2014). Twenty soil cores were collected in total per plot using an auger (10 cm depth * 4.5 cm diameter). There were five sampling points from which four subsamples were collected to produce one composite sample per plot.

3.3 Soil Characteristics

Fresh homogenised soil samples were dried at 105°C for 48 h and gravimetric water content (GWC) determined. Soil organic matter (SOM) was estimated from loss on ignition, at 550°C for 4 h on oven-dried soils (Tan, 2005). Fresh soil was air dried at 30°C, ground to pass 2 mm mesh sieve and homogenised for all subsequent analyses. Soil texture was determined using the pipette method based on oven-dry weight. Particle sizes were categorised as: clay <2 μm, silt 2–20 μm and sand 63–2000 μm (Tan, 2005). Soil organic carbon (SOC) was measured using a Leco SC-144DR Carbon/Sulfur Analyser at 840°C (Leco Corporation; USA). Quantification of pH was done in diH_2O solution (1:5, soil:water ratio) (Tan, 2005) and read on a pH meter (Jenway 3510, UK).

The soil nutrient status was determined by measuring the standard macronutrients required for plant growth: phosphorus (Olsen-P), extractable potassium (K^+) and magnesium (Mg^{2+}).

In addition, extractable calcium (Ca^{2+}), total nitrogen (%tN) and total sulfur (%tS) were also measured. In Experiment-1, the nutrient status of soil was measured four times, twice per crop season, once in Spring and again in Autumn. In Experiment-2, soil samples were collected once per crop season after harvest in autumn. Extractable-K^+, -Mg^{2+} and -Ca^{2+} ions were extracted with 1 M NH_4NO_3 (MAFF/ADAS, 1986). Their fractions were analysed by Atomic Absorption Spectrometry. Phosphorus was extracted using the Olsen-P method in 0.5 M $NaHCO_3$ solution adjusted to pH 8.5 at 20°C. Absorbance of the final blue complex concentration was read using Jenway 6305 UV/Vis (USA) spectrophotometer at 880 nm (Tan, 2005).

3.4 Quantification of Microbial Biomass Chloroform Fumigation

Microbial biomass carbon and nitrogen were analysed using the chloroform fumigation direct extraction method for all fresh soil samples (Vance et al., 1987; Brookes, 2001), using two 10 g aliquots of fresh soil from each composite sample. Microbial biomass carbon (MBC) and nitrogen (MBN) were quantified on a TOC (Analytik Jena AG TOC/TN, U.K.) and results calculated by subtracting the fumigated by the non-fumigated samples using the formulae:

$$MBC = \frac{(F_C - nF_C)}{K_C} \qquad MBN = \frac{(F_N - nF_N)}{K_N}$$

Where: F = fumigated sample, nF = non-fumigated sample, K = constant (K_C = 0.45, K_N = 0.54) (Jenkinson et al., 2004).

3.5 Crop Analysis

Parameters associated with crop productivity such as grain yield, thousand grain weight (TGW), protein content of grain and biomass and cover crop aboveground biomass were quantified. Cash crop parameters were measured twice during this two-year study, after harvest in autumn of both Experiments 1 and 2. Grain of *Triticum aestivum*, var. Mulika (spring wheat) and *Avena sativa* var. Mascani (winter oats) were directly bagged in the field during harvest using a plot harvester for each plot and subsequently weighed to calculate yields per replicate (t ha^{-1}). Three sub-samples of grain were collected using a 0.5 L jug to sample from the grain bags. Grain was dried at 60°C and moisture content determined (w/w, %) using a DICKEY-john GAC® 2500-UGMA grain analysis computer (Auburn, USA). Afterwards, Thousand Grain Weight (TGW, g) was quantified by randomly collecting and weighing 100 grains and repeating the process five times for each dried subsample. The mean weight was then used to estimate the weight of a thousand grains. All reported yields (t ha^{-1}) and TGW values (g) were standardised to 14.5% moisture content (Mulvaney and Devkota, 2020).

Cover crop, *Raphanus sativus* and *Vicia* sp., aboveground biomass was sampled using the quadrat method. On each GM plot, three quadrats of 1 m^2 were placed randomly within each plot, 2 m away from the edge of each plot, and used to cut whole plants 10 cm from the ground. The plants were dried at 60°C and aboveground biomass quantified (t ha^{-1}).
The cereals grain and cover crop biomass were separately ground to 0.5 mm. Total N (%tN) analysis was conducted by the dry combustion method (950°C) using Leco FP528 (EVISA, EU). Protein content was calculated by using the conversion factor of 6.25, which assumes that 16% of protein content is nitrogen (Tomé et al., 2019).

Table 1: Field record of both experiments

Field Information						Manufactured Fertilisers				Organic Manures					Crop Protection		
Field Name	Field Area	Drilling Date	Crop	Rate	Drill Type	Date	Type	Nutrients (%)	Rate	Date	Manure Type	Rate (t ha^{-1})	N Content (%)	Method of Application	Date	Active Ingredient	Rate
Both experiments	2.5 ha					07/04/2017	LimeX70 ($CaCO_3$ precipitate)	52% Ca, 1% P, 0.7% Mg, 0.6% S	12.5 Mg ha^{-1}								
Experiment 1, FYM + N-fert treatment	6 x (200 x 6 m) plots	14/04/2017	Spring wheat, *Triticum aestivum* , var. Mulika (with Beret Gold seed dressing)	150 kg ha^{-1}	Weaving GD3001T Direct Disc Drill	04/05/2017	Nitram	34.5% N	150 kg ha^{-1}	13/04/2017	Cattle FYM	40 Mg ha^{-1}	2.2	Surface spread and incorporated by discing	20/09/2017	Ally Max SX and Duplosan	42 g ha^{-1} and 1 L ha^{-1} in water 200-240 L ha^{-1}
Experiment 1, N-fert treatment	6 x (200 x 6 m) plots	14/04/2017	Spring wheat, *Triticum aestivum* , var. Mulika (with Beret Gold seed dressing)	150 kg ha^{-1}	Weaving GD3001T Direct Disc Drill	04/05/2017	Nitram	34.5% N	125 kg ha^{-1}						20/09/2017	Ally Max SX and Duplosan	42 g ha^{-1} and 1 L ha^{-1} in water 200-240 L ha^{-1}
Experiment 1, Cover Crops treatment	6 x (200 x 6 m) plots	14/04/2017	Fodder radish (*Raphanus sativus*) and vetch (*Vicia sp.*)	29 kg ha^{-1}, seed ratio of 50:50	Weaving GD3001T Direct Disc Drill												
Experiment 2, N-fert treatment	9 x (24 x 6 m) plots	14/04/2017	Spring wheat, *Triticum aestivum* , var. Mulika (with Beret Gold seed dressing)	150 kg ha^{-1}	Weaving GD3001T Direct Disc Drill	04/05/2017	Nitram	34.5% N	125 kg ha^{-1}						20/09/2017	Ally Max SX and Duplosan	42 g ha^{-1} and 1 L ha^{-1} in water 200-240 L ha^{-1}
Experiment 2, Cover Crops treatment	8 x (24 x 6 m) plots	14/04/2017	Fodder radish (*Raphanus sativus*) and vetch (*Vicia sp.*)	29 kg ha^{-1}, seed ratio of 50:50	Weaving GD3001T Direct Disc Drill												
Experiment 1 and 2, FYM + N-fert, N-fert, and Cover Crops treatments	18 x (200 x 6 m) plots	18/10/2017	Winter oats (Avena sativa var. Mascani with Beret Gold seed dressing	160 kg ha^{-1}	Weaving GD3001T Direct Disc Drill	09/11/2017	Muriate of potash	60% KCl	100 kg ha^{-1}						16/10/2017 and 23/10/2017	RoundUp Bioactive GL	1.5 L ha^{-1} in 200 L of water
Experiment 1 and 2, FYM + N-fert, N-fert, and Cover Crops treatments															26/10/2017	Slug pellets (3% metaldehyde	7 kg ha^{-1}
Experiment 1 and 2, FYM + N-fert, N-fert, and Cover Crops treatments						07/05/2018	Calcium nitrate fertiliser	15.5% N + 26.3% $Ca^{2+}O^{2-}$	100 Kg ha^{-1}						19/04/2018	Nevada, Dow AgroScience	1.0 L ha-1, 200 L of water ha-1

3.6 Statistical Analysis

Statistical analyses were conducted in R-Studio (R Core Team, 2022), and the packages “correlation”, “corrplot”, “tidyverse”, “ggpubr”, “rstatix”, “rcompanion”, “Hmisc”, and “psych” (Wickham et al., 2019; Kassambara, 2020 and 2021; Mangiafico, 2021; Wei et al., 2021; Harrell Jr, 2022; Makowski et al., 2022; Revelle, 2022).

Raw data was visualised using boxplots, and normality of data was tested using the Shapiro-Wilk test and QQ-plots. Tukey’s ladder transformation of data (Zuur *et al.*, 2009) was used where data did not satisfy the necessary assumptions of linear regression. The transformed variables were: GWC in May-2018 and MBC with the transformation applied = x^{λ}; P in October-2017 with the transformation applied = log(x); P in May-2017, %tN, %tS, Ca in October-2017, %tS, P in May and October-2018, Mg in November-2017, Clay, Silt, Mg in November-2018 with the transformation applied = $-1 * x^{\lambda}$.

Linear regression models were run with continuous response variables (i.e. SOC, SOM, MBC, MBN, tN, tS, GWC, pH, Olsen-P, K^{+}, Mg^{2+}, Ca^{2+}, grain yield, TGW, grain and cover crop protein content or cover crop biomass), which were the target variables, with treatments (categorical variable: FYM, GM, SP) as the explanatory variables for each temporal observation (May, October or November 2017-2018), and/or with soil texture included (clay, silt and sand).

Relationships between response variables and both the interaction and main effects of treatment and sampling period with soil texture were assessed using factorial ANOVA. Tukey’s Honest Significant Difference *post-hoc* tests (Tukey HSD) were computed on significant models ($p \leq 0.05$). Results are presented as means ± standard error unless indicated otherwise.

Factorial ANOVA regression models were run with SOC as the continuous response variable with treatment (categorical variable: FYM, GM, SP) as the explanatory variable for each temporal observation (May, October, or November 2017-2018). Further explanatory variables were MBC and MBN, Ca^{2+} and tN, pH and GWC or soil texture. Tukey Honest Significant Difference *post-hoc* tests were computed on significant models ($p \leq 0.05$) for all individual comparisons. Pearson correlation test was applied between pairs of variables, i.e. SOC, SOM, tN, tS, GWC, pH, Olsen-P, K^{+}, Mg^{2+}, Ca^{2+}, clay, silt and sand. The p-value was adjusted to the Holm method (1979) and set to significant level at <0.05. Stronger correlations near -1 or 1, and a value of $r = Ø$ indicates independence of variables.

4 Results

4.1 Soil Properties

Soil Texture

Most plots in Experiment-1 were on sandy loam (48.4%) and sandy clay loam (45.2%). Clay loam soil made up 4.0% and loamy sand 2.4% of the soil types. Experiment-2 was dominated by loamy sand soil (74%) and the remaining 26% was sandy loam (Table 3).

Table 2: Soil texture classes identified in each experiment investigating the effects of N-fertiliser, FYM and cover crops.

Texture Class	Experiment-1 (%)	Experiment-2 (%)
Loamy Sand	2.4	73.5
Sandy Loam	48.4	26.5
Sandy Clay Loam	45.2	0.0
Clay Loam	4.0	0.0

pH and GWC

May-2017 was the only period that exhibited significant pH differences between SP and FYM ($p = 0.01$) or GM ($p = 0.003$) in Experiment-1. No significant differences in pH were observed in Experiment-2 between treatments over time, (Nov-2017 $p = 0.8$ and Nov-2018 $p = 0.2$) (Table 4). No significant differences were observed in soil gravimetric water content (%GWC) in either Experiment-1 or 2.

Table 3: Mean soil pH values ± standard deviation for Experiment 1 and 2 (E1 n = 6; E2 SP n = 9, GM n = 8) investigating the effects of N-fertiliser, FYM and cover crops.

	Experiment-1				Experiment-2	
Treatment	May-17	Oct-17	May-18	Oct-18	Nov-17	Nov-18
SP	7.0* (±0.12)	6.6 (±0.19)	6.8 (±0.26)	6.6 (±0.36)	6.2 (±0.24)	6.2 (±0.28)
FYM	6.8 (±0.09)	6.6 (±0.07)	6.8 (±0.28)	6.6 (±0.23)		
GM	6.7 (±0.22)	6.8 (±0.38)	6.9 (±0.17)	6.7 (±0.28)	6.2 (±0.26)	6.4 (±0.36)

Macronutrients in Soil

Total nitrogen increased soon after FYM (FYM characteristics: OM = 71%, %tN = 2.2%) was spread and incorporated in May-2017 (Fig. 1) although this was marginally non-statistically significant (p = 0.06). Yields obtained in FYM were comparable to SP, which received synthetic N-fertiliser alone (i.e. no manure; Fig. 1). While the GM treatment did not receive N-fertiliser in 2017 it exhibited equivalent concentrations of %tN in October-2017, showing an increase from 0.18 to 0.21%. This result was analogous to SP where %tN increased from 0.18 to 0.22%.

An increase in Olsen-P in the SP and FYM treatments of Experiment-1 sampled in May-2018 and October-2018 was observed, but an increase in the Olsen-P in the GM treatment was only seen in October-2018 (Fig. 1). It was found that %tN effect on Olsen-P was temporal, i.e. observed in October 2017 (p = 0.03) and 2018 (p = 0.04), with a lag period from N inputs, and related to spatial variation as it was only observed in Experiment-1.

FYM in Experiment-1 and GM (*R. sativus* and *Vicia sp*. mix cover crop) in Experiment-2 resulted in increased potassium (K^+) concentration. In Experiment-1, 50% more extractable-K^+ (mg K^+ L^{-1}) was measured in the FYM (p = 0.01) treatment than in the SP or GM treatments in May-2017, on average, 3 weeks after incorporating FYM (Fig. 1). This concentration continued to be significantly higher in October 2017 (p= 0.01) and 2018 (p = 0.002). The effect from the cover crop was only observed in GM in Experiment-2 in November-2018 (p = 0.001).

Extractable-Mg^{2+} (mg Mg^{2+} L^{-1}) was only significantly different between SP and GM in November-2018 (p = 0.04) in Experiment-2 (Fig. 1). The concentration of extractable-Ca^{2+} was higher across all treatments in May-2017 in comparison with other periods (Fig. 1). A notable effect of FYM on sulfur (%tS) concentration in soil was observed in October-2018, results were highly variable and not statistically significant (Fig. 1).

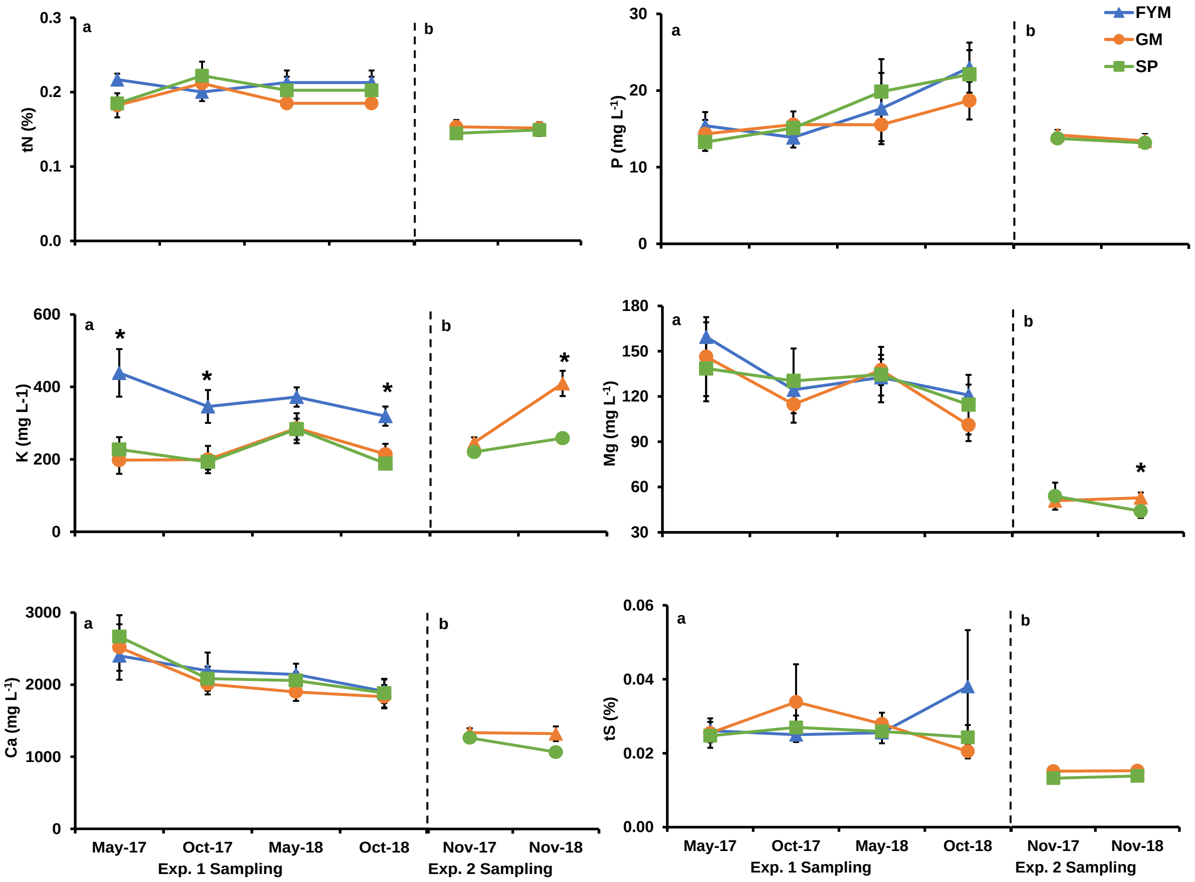


*Figure 1: Experiment 1 and 2 (**a** and **b**) mean results of soil % total nitrogen (%tN), phosphorus (mg Olsen-P L^{-1}), potassium (mg K^{+} L^{-1}) and magnesium (mg Mg^{2+} L^{-1}), extractable calcium (mg Ca^{2+} L^{-1}) and total sulfur (%tS). Four sampling sessions (May and October 2017-2018) were conducted for Experiment-1 (**a**), and two sampling sessions (November 2017-2018) for Experiment-2 (**b**). Treatments: Farmyard manure (FYM in blue); Green manure (GM in orange); Standard practice (SP in green). Lines show means; bars show ± standard error of the means. Asterisk (*****) show significant differences between treatments. Experiment-1 n = 6; Experiment-2 GM n = 8, SP n = 9.*

4.2 Microbial Biomass

Experiment-1

There was a significant interaction between the different treatments and sampling period ($p = 0.03$; Fig. 2). MBC was significantly higher in the FYM May-2017 treatments in comparison to GM (May-Oct 2017-2018 $p < 0.001$, $p = 0.01$, $p = 0.01$ and $p < 0.001$) and SP (May-Oct 2017-2018 $p = 0.01$, $p = 0.001$, $p = 0.005$, $p < 0.001$) and FYM (Oct-2018 $p < 0.001$). No significant interaction effect was observed between treatment and sampling period for the amount of MBN ($\mu g\ g^{-1}$) ($p = 0.5$) (Fig. 2). There was, however, an effect observed from treatments ($p = 0.001$) or sampling periods ($p < 0.001$). In May-2017, MBN was significantly higher in FYM in Oct-May 2017-2018 than in the GM treatment ($p = 0.004$, $p = 0.004$ respectively) or SP ($p = 0.004$, $p = 0.004$ respectively). It was also lower in the GM Oct-2018 treatment than in FYM Oct-2017 ($p = 0.02$) and May-2018 ($p = 0.02$).

Experiment-2

A significant response in MBC ($p = 0.03$) and MBN ($p = 0.04$) to treatments and sampling period were observed (Fig. 2).

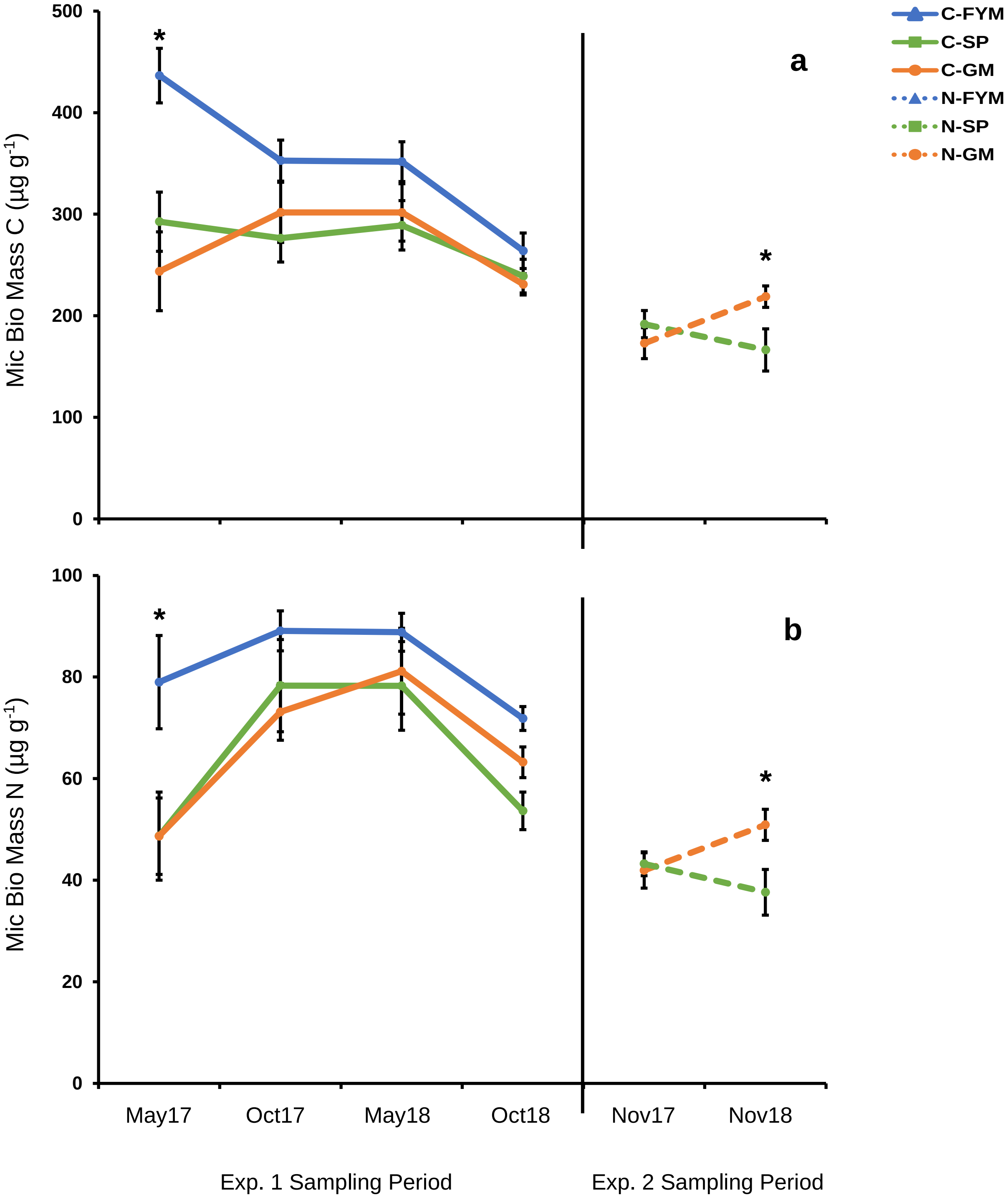


Figure 2: **a)** Microbial biomass **C**arbon (µg Mic **C** g^{-1}) and **b) N**itrogen (µg Mic **N** g^{-1} of soil) change over time from the start of Experiment-1 (solid lines) in May 2017 to completion in October 2018, and Experiment-2 (dotted lines) in November 2017 and 2018. Experiment-1 treatments: FYM = Farmyard Manure, n = 6; SP = Standard Practice, n = 6; GM = Green Manure, n = 6; ± standard error. Experiment-2 treatments: SP = Standard Practice, n = 9; GM = Green Manure, n = 8; ± standard error. Asterisks symbolise significant differences between groups that were identified from Tukey HSD *post-hoc* test.

4.3 SOC and SOM Response to Treatments

The same pattern was observed with both SOC and SOM over time (Fig. 3) with no significant interaction effect with either variable. There was no statistical interaction between Experiment-1 treatment and sampling period for either SOC or SOM ($p = 0.8$, $p = 1.0$, respectively). There were no significant treatment effects within the first year of Experiment-2 (2017) nor were detectable legacy effects (2018) on the proportion of either SOC ($p = 0.7$) or SOM ($p = 0.8$). Therefore, the decision to use only the SOC variable going forward was taken.

4.4 SOC and Interaction Effects

Experiment-1

A change in microbial biomass carbon (MBC) could significantly affect the concentration of SOC ($p = 0.001$). The interaction between treatments, sampling period and MB-Nitrogen (MBN) was also significant ($p = 0.04$). However, no significant pairwise comparisons were identified. Treatment and sampling period, with or without calcium (Ca^{2+}) or total nitrogen (tN), exhibited a significant interaction with Ca^{2+} ($p < 0.001$) and with the interaction between tN and treatment ($p = 0.03$) and sampling period ($p = 0.03$). Once again, no significant pairwise comparisons were computed. Treatment and sampling periods showed a significant interaction between gravimetric water content (GWC, $p = 0.003$) or pH ($p = 0.02$) with SOC but no pairwise comparisons were significant. The effects of soil texture were also tested and the amount of sand ($p = 0.02$) or silt ($p = 0.02$) were associated with the concentration of SOC, but not pairwise comparisons showed any significant treatments interaction with or without sampling period.

Experiment-2

No significant interaction effects between treatment, sampling period and MBC ($p = 0.1$) or MBN ($p = 0.5$) on SOC were observed. Similarly, no significant interactions were found when Ca^{2+} ($p = 0.9$) and tN ($p = 0.6$) were added to the model instead of microbial biomass. Significant associations between either Ca^{2+} ($p < 0.001$) or tN ($p < 0.001$) with SOC were detected. A significant treatment effect ($p = 0.002$) was but the interaction between either treatment and Ca^{2+} or tN were not observed.

The effect of soil texture on SOC was associated with either the proportion of clay ($p < 0.001$) or sand ($p < 0.001$) in soil, but not by the interaction effects with treatments and sampling periods ($p = 0.7$, $p = 0.5$ respectively) (Fig. 4). Similarly, no significant interaction effects were computed between soil texture with pH values ($p = 0.9$) and GWC ($p = 0.4$).

However, there was a significant response from SOC to pH ($p = 0.01$) or to GWC ($p < 0.001$), but not determined by treatment effect.

4.5 Correlations Between the Pairs

The correlation matrix found many significant associations between pairs both unidirectional and following an opposite trend (Fig. 5). Strong positive correlations were found between the clay and SOM ($r = 0.8$), Ca^{2+} ($r = 0.8$), Mg^{2+} and %tN ($r = 0.7$). Whereas, as the amount of sand increased so do other properties decreased either moderately (i.e. MBC or MBN or %tS, $r = -0.5$) or strongly (i.e. SOC or pH, $r = -0.6$; %tN, $r = 0.6$; SOM or Ca^{2+} or Mg^{2+}, $r = 0.8$).

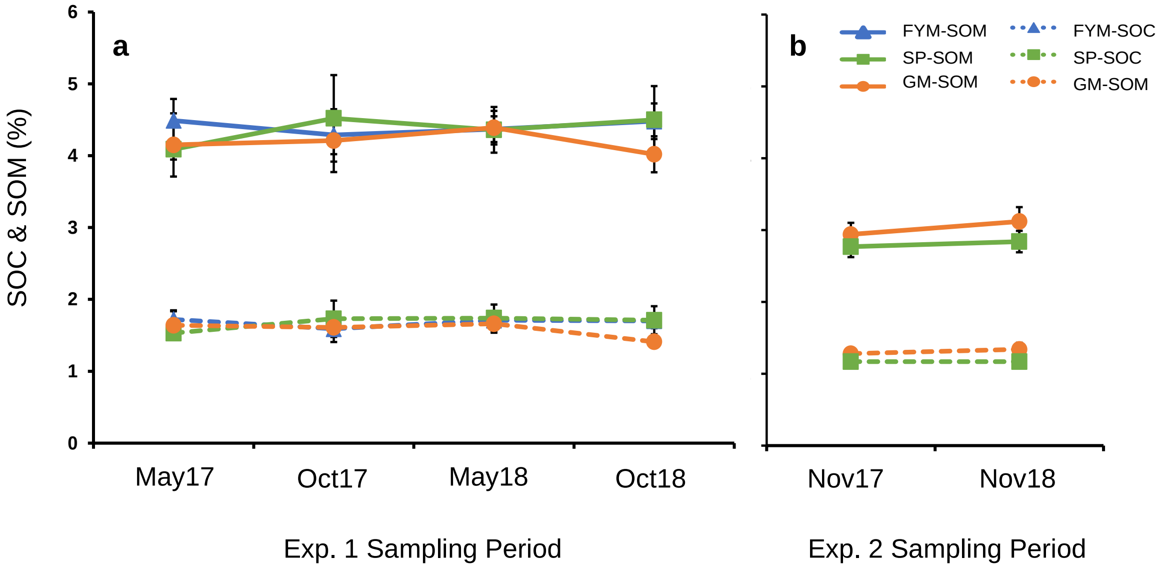


Figure 3: Time series of SOC and SOM results from Experiment 1 (**a**) and 2 (**b**). Soil sampling was done in **a**) May and October 2017-2018, and in **b**) November 2017-2018. The treatments were Farmyard Manure (FYM), Green Manure (GM), and Standard Practice (SP). SOC is represented by the dotted lines, and SOM by the full lines. Plot **a** n = 6, Plot **b** GM n = 8, SP n = 9, ±SEM.

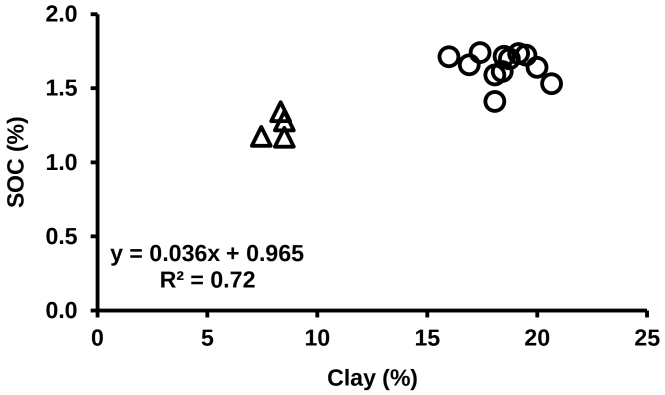
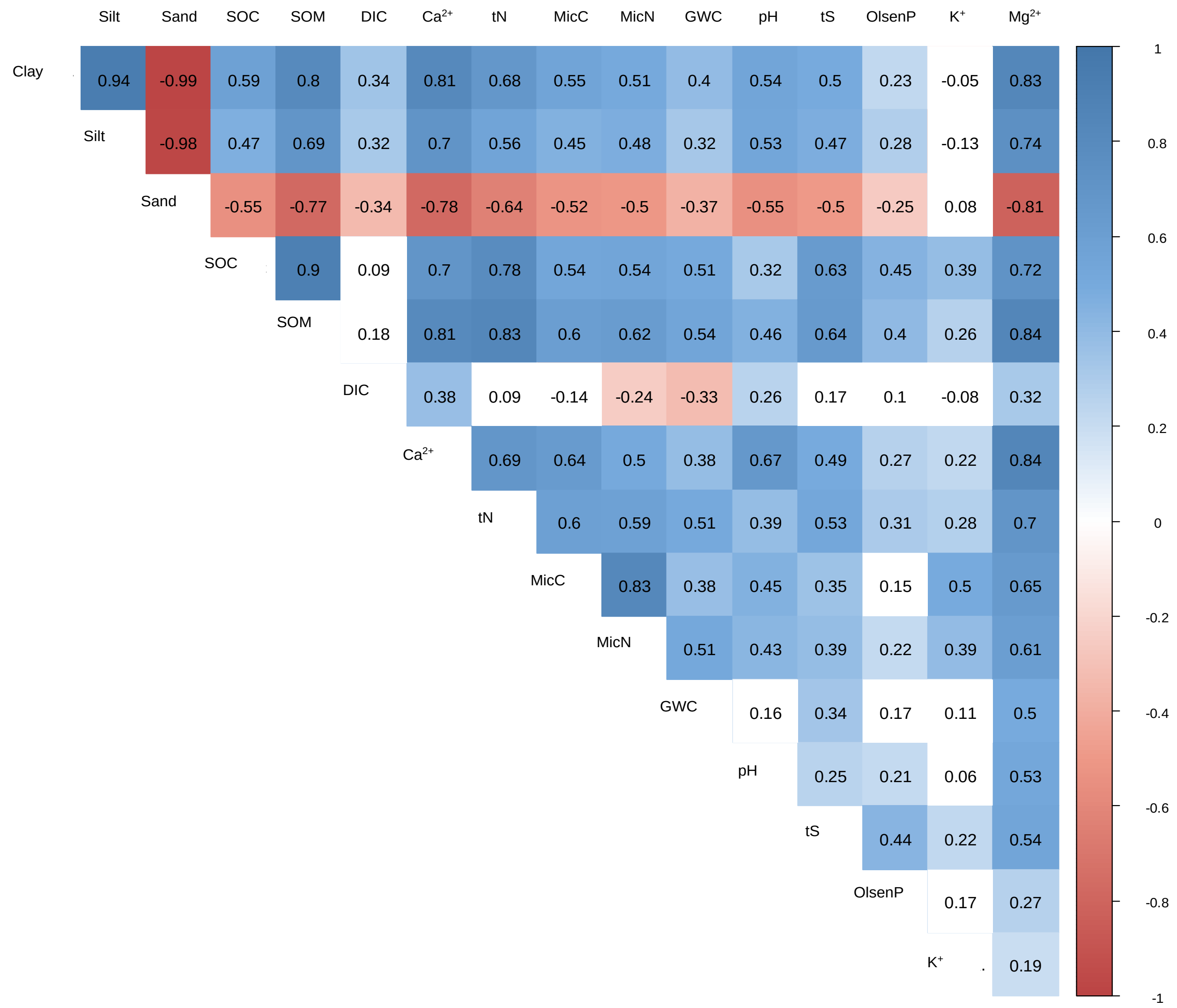


Figure 4: Regression plot indicating the linear relationships between the amount of clay particles in soil texture and soil organic carbon (SOC) using treatment mean data from both Experiments 1 (in circles) and 2 (in triangles) sampled over the two-year experimental period.



	Silt	Sand	SOC	SOM	DIC	Ca^{2+}	tN	MicC	MicN	GWC	pH	tS	OlsenP	K^+	Mg^{2+}
Clay	0.94	-0.99	0.59	0.8	0.34	0.81	0.68	0.55	0.51	0.4	0.54	0.5	0.23	-0.05	0.83
Silt		-0.98	0.47	0.69	0.32	0.7	0.56	0.45	0.48	0.32	0.53	0.47	0.28	-0.13	0.74
Sand			-0.55	-0.77	-0.34	-0.78	-0.64	-0.52	-0.5	-0.37	-0.55	-0.5	-0.25	0.08	-0.81
SOC				0.9	0.09	0.7	0.78	0.54	0.54	0.51	0.32	0.63	0.45	0.39	0.72
SOM					0.18	0.81	0.83	0.6	0.62	0.54	0.46	0.64	0.4	0.26	0.84
DIC						0.38	0.09	-0.14	-0.24	-0.33	0.26	0.17	0.1	-0.08	0.32
Ca^{2+}							0.69	0.64	0.5	0.38	0.67	0.49	0.27	0.22	0.84
tN								0.6	0.59	0.51	0.39	0.53	0.31	0.28	0.7
MicC									0.83	0.38	0.45	0.35	0.15	0.5	0.65
MicN										0.51	0.43	0.39	0.22	0.39	0.61
GWC											0.16	0.34	0.17	0.11	0.5
pH												0.25	0.21	0.06	0.53
tS													0.44	0.22	0.54
OlsenP														0.17	0.27
K^+															0.19

Figure 5: Correlogram of correlation coefficients for pairs of variables from both Experiment 1 and 2. Positive correlations are displayed in blue and negative correlations in red. The intensity of the colour is proportional to the correlation coefficient. The stronger the correlation by being nearer to r = -1 or r = 1, the darker the boxes are. The white boxes symbolise no significant quantifiable correlation between the pairs.

4.6 Cereals

Experiment-1

The average spring wheat 2017 yield was 1.2 t ha^{-1} (± 0.2 SD) in both the SP and FYM treatments. There were no significant differences in yield ($p = 0.4$) (Fig. 6), TGW ($p = 0.9$) or grain protein ($p = 0.6$) between the SP and FYM 2017 treatments. In 2018, the yields of winter oats, TGW and grain protein were not significantly different either between the SP and FYM ($p = 1.0$, $p = 0.4$, $p = 0.1$, respectively) or GM treatments ($p = 0.3$, 0.5, 0.3, respectively). The average yield was 5.1 t ha^{-1} on both SP (± 0.5 SD) and FYM (± 0.7 SD) treatments, and 5.4 t ha^{-1} (± 0.8 SD) in the GM treatment.

Experiment-2

Harvest 2018 resulted in significantly greater yields of winter oats ($p = 0.01$) and respective grain protein ($p = 0.02$) in the GM treatment in comparison with SP (Fig. 6). However, yields on this slope side of the field were much lower than the UK average; SP = 2.1 t ha^{-1} and GM = 2.5 t ha^{-1}. TGW was significantly lower in the GM ($p < 0.001$) treatment in comparison with SP with a reduction of 4.4 g (± 0.1) on average.

4.7 Cover crop

Experiment-1 and 2

The aboveground biomass of the cover crops (*R. sativus* and *Vicia sp*. mix) was greater in Experiment-2 than in Experiment-1 (Fig. 6). However, the difference was marginally non-significant ($p = 0.06$). No significant difference in protein content of the cover crop aboveground biomass was identified, with results ranging from 24% ±0.3 in Experiment-1 and 23% ±0.2 in Experiment-2.

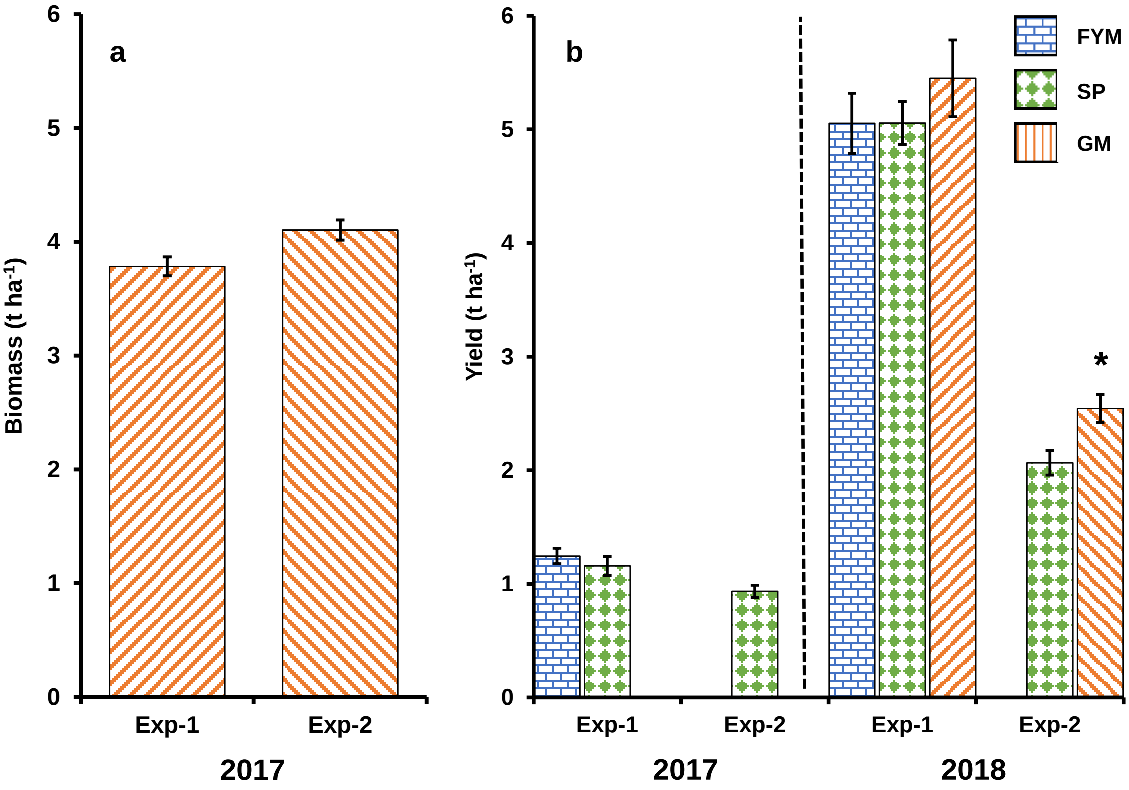


Figure 6: **a)** Aboveground biomass (t ha^{-1}) of Raphanus sativus and Vicia sp. cover crop mix from both Experiments 1 and 2 (Exp-1 and Exp-2) in 2017 crop season (n = 6 and n = 8, respectively), and **b)** grain yields for both experiments of two crop seasons, 2017 and 2018. In 2017, Spring wheat (Triticum aestivum) was only drilled in the Standard Practice (SP) and Farmyard Manure (FYM) Exp-1 treatments, and in Exp-2 SP treatment; a cover crop was drilled in the GM plots – hence the missing columns there. Winter oats (Avena sativa) were direct drilled in 2017 and harvested in Summer 2018 (Exp-1and Exp-2) on all treatment plots. Columns show means (E1 n=6; E2, SP n = 9, GM n = 8); Error bars show ± standard error of the mean. Asterisk (*) symbolises significant difference ($p < 0.05$) between treatments.

4.5 Discussion

Focus has been increasing on identifying optimum management practices to increase soil carbon stocks, reduce fertiliser inputs and associated greenhouse gas emissions, (NFU, 2019; Searchinger *et al.*, 2019; Amelung *et al.*, 2020; CCC, 2020). Thus, understanding the short-term interaction between inputs to soil in a no-till arable system on SOC and SOM, combined with microbial biomass and soil properties such extractable Ca^{2+} (a key factor in SOM stabilisation (Rowley *et al.*, 2018) and other ions, total-Nitrogen (%tN), pH, gravimetric water content (GWC) and soil texture is key to developing best management practices. Macronutrients were selected for their role in crop growth, and which can be measured routinely in accordance with standard agricultural procedure (Lines-Kelly, 1992; Defra, 2010). Additionally, GWC and pH values were quantified because they influence the solubility and availability of nutrients (Rowell, 1994). The results presented here demonstrated that the type of soil organic amendments, FYM or cover crops, at the amounts used for this study (Experiment-1: 8.9 Mg OM ha^{-1} for FYM and 3.8 Mg OM ha^{-1} for 50:50 cover crops; Experiment-2: 4.1 Mg OM ha^{-1} for CC) did not significantly impact SOC but did impact microbial biomass and soil nutrient status over a two-year period. Soil characteristics (i.e. %clay, %sand or %silt) were often a better predictor of SOC and MBC differences than the type of organic amendment. This result supports the findings of other studies such as Schmidt *et al.* (2011) and Lehmann and Kleber (2015) who reported that ecosystem properties such as conditions for enzymatic accessibility were more effective predictors of organic matter turnover than the chemical properties of the organic amendments. Response to treatments was influenced by spatial and temporal variations as observed with the variable response of the nutrient status of soil. Other studies have also confirmed that organic amendments added to soils are mineralised quickly, influencing the availability of nutrients for crop uptake (Watts et al., 2006; Gan et al., 2020; Gewin, 2020; Bullock et al., 2021; Berthelin et al., 2022). Fertiliser costs can be prohibitive to buy but are essential to produce profitable yields and ensure food security. FYM and/or cover crops could be a viable method in ensuring food productivity whilst aiding the reduction of synthetic fertilisers use helping prevent or reduce environmental pollution. However, their efficacy is highly influenced by spatial heterogeneity. The results presented here provide an arable system case study on the short-term effects of conversion to no-till under three different management practices, namely FYM, cover crops and N-fertiliser alone.

SOC Response

Soil management practices promoted as having potential to increase soil C stocks are often associated with reduced tillage, retaining of crop residues/stubble, crop rotation, sowing of N-fixing plants, and incorporating manures (Hernanz et al. 2009; Mutegi et al., 2011;

Amundson and Biardeau, 2018; Abdalla et al., 2019; Baveye et al., 2020). However, these practices do not always lead to increased C stocks (Buysse et al., 2013; Powlson et al., 2014; Mary et al., 2020), as was observed in this study. It has been suggested that, in the long-term, occasional tillage might be needed to enhance the ability of C stock stratification because gains have been limited to the top 10 cm of soil in no-till systems (Minasny et al., 2017). There are, however, other benefits that can be incentivised by these practices like increased microbial abundance associated with ecosystem resilience (Zuber and Villamil, 2016), and other examples outside the scope of this paper such as increased earthworm abundance (Briones and Schmidt, 2017) and improved soil structure (Ayoubi et al., 2012; Buysse et al., 2013).

Increases in SOC are expected to be substantial on sites where initial C stocks are low (Six and Jastrow, 2002; Virto et al., 2012; Amelung et al., 2020). However, soil has limited capacity for storing C which is influenced by its textural properties, in particular clay and silt content (Six and Jastrow, 2002; Schweizer et al., 2021). Studies have found that the level of soil disturbance, i.e. tilling or not, had no impact on SOC stocks in long-term experimental sites when the soil layer was measured to 40 cm depth (Valboa et al., 2015; Meurer et al., 2018; Mary et al., 2020). Stratified sampling showed that C accumulated in the topsoil at 5 cm depth in a no-till study (Mary *et al.,* 2020) and at 10 cm depth in a reduced tillage study (Valboa et al., 2015). This was offset by the lower C stocks being accumulated deeper in comparison with full inversion tillage. SOC stocks were 22.9 t C ha^{-1} after 47 years in the former no-till treatment with a baseline of 16 t C ha^{-1} in a silty clay loam soil. These values were analogous to the ones estimated in this study, 22.0 t C ha^{-1}, in Experiment-1 where the soil was classified as sandy clay loam corresponding to both being heavy textured soil types (bulk density = 1.33 g cm^{-3}) with clay content above 20% (Rowell, 1994). Whereas in the latter study, in 12 years, it increased from ~13 t C ha^{-1} to ~16 t C ha^{-1} in a sandy loam medium soil. Xiong *et al.* (2015) found that SOC accumulation was on average 46.6 t C ha^{-1} (20 cm depth, estimate of 23.3 t C ha^{-1} in the top 10 cm) in light soils (bulk density = 1.33 g cm^{-3}). In the current study, increases in SOC stocks were more likely to be observed on patches with light and medium texture soil classes, but this was not recorded during the two-year study period. Results from other studies suggest that the heterogeneity of soil in the current study may have led to increases being observed in the topsoil (10 cm depth) in the patches with the textural class of loamy sand (17.4 t C ha^{-1} Experiment-2 estimate) and sandy loam (estimated at 9.9 t C ha^{-1} in Experiment-2 and 13.2 t C ha^{-1} in Experiment-1). However, one study contradicts the correlation between soil texture and SOC stocks. The authors reported that SOC increased by 6.7% (30 cm depth) following the conversion from full inversion tillage to no-till, but this was not associated with the proportions of clay, sand or silt (Virto et al., 2012). Other factors in addition to soil texture influence SOC stocks, such as microbial-SOC dynamics, land-management, precipitation and temperature, and these should be considered to better understand the mechanisms behind changes in SOC stocks (Powlson et al., 2011).

Microbial Biomass

Results presented here confirm that microbial biomass quantification provides early insights into changes in management practices where other changes in soil properties such as SOC or SOM may take years to show a significant response to regular organic inputs (Powlson et al., 1987; Brookes, 2001; Erkossa and Stahr, 2015; Heuck et al., 2015). Incorporating FYM into soil offers a readily available source of labile organic matter that triggers processes such as microbial decomposition and nutrient mineralisation and immobilisation to occur (Brookes, 2001; Gan et al., 2020; Liang et al., 2022). Regular organic inputs such as FYM introduces C into the system, improves soil structure and water holding capacity, which all are conducive to increasing SOC stocks (Powlson et al., 2011). However, benefits to SOC can quickly dissipate due to sporadic inputs over a short period of time as reported by this study (Berthelin et al., 2022).

Ca^{2+} Effect

Calcium plays an important role in the stabilisation of SOC through cationic bridging and its loss as a result of leaching can reduce soils' productivity potential (Eldor, 2016; Zamanian et al., 2021). A positive association between Ca^{2+} and SOC was detected in both experiments of this study, possibly linked to Ca-bridging (Rowley et al., 2018). Similarly, studies have found that liming led to an increase in SOC accumulation within aggregates possibly due to increased Ca^{2+} derived from the liming agents (Six et al., 2004; Briedis et al., 2012).

Nutrient Status of Soil

Adopting no-till along with soil amendments such as fertilisers and manures did benefit the nutrient status of soil albeit influenced by spatial and temporal variations. For example, the greater increased concentration of extractable-Mg^{2+} in Experiment-2 suggests a legacy effect from cover crops. Magnesium is comparatively mobile in soils in contrast with other cations like K^+, Ca^{2+}, and NH^{4+}, and forms weaker bonds to soil mineral charges (CEC) (Sparks, 2015). However, a meta-analysis concluded that the concentrations of Mg^{2+} quantified in Experiment-2 (i.e. < 60 mg L^{-1}) were not adequate for crop growth (Wang *et al.*, 2020). This finding may explain the reduced yields thereof the sloped experimental site due in part to Mg deficiency. The higher concentration of extractable-Ca^{2+}, across all treatments in May-2017, in comparison with other periods, likely occurred in response to liming. In agriculture, liming (spreading of Limex70 here, a $CaCO_3$ precipitate) is done to neutralise soil acidity. However, it can lead to a cycle of necessary remediations because acidification of soil through N-fertilisation can occur with CO_2 being release to the atmosphere and Ca^{2+} leaching (Zamanian et al., 2021). Acidification due to N-fertiliser addition was not observed in this study as shown by the pH values that remained similar across sampling periods.

Plant uptake of both K^+ and Mg^{2+} and subsequent release has been found to be higher under legumes (e.g. *Vicia sp*.) and brassicas (e.g. *R. sativus*) than in cereals, which is linked to differences in nutrient requirements leading to greater immobilisation (Groffman *et al.,* 1987; Cardoso *et al.*, 2013; Wendling *et al.*, 2016). The effect from the cover crop was only observed in the GM treatment of Experiment-2 in November-2018, which may have been influenced by soil texture. This agrees with Taiwo *et al.* (2018) who reported that %clay was positively correlated with fixed K^+, whereas extractable-K^+ correlated well with %sand. However, soluble nutrients like K^+ can quickly leach from sandy soils if not taken up by plants (Groffman *et al.*, 1987) and this could be a consideration when using cover crops for slow-release nutrient provision, which are less leachable than K applied as potash. The dry summer months of 2018 (Defra, 2019) could have aided the concentration of K^+ to be retained in the soil of Experiment-2 which would otherwise leach following periods of rainfall. The risk of nutrient runoff and leaching can be minimised if soil amendments are applied in dryer periods because there is a greater potential in periods of heavy-rainfall particularly from sandy and/or sloping land (Yao *et al.*, 2021).

The FYM treatment of Experiment-1 offered a supply of potassium (K^+), with potential in helping reduce fertiliser requirements. The average 50% more extractable-K^+ in the former was measured in the FYM treatment than in the SP or GM treatments in May-2017, three weeks after incorporating FYM. This effect was still observable in October 2017 and 2018. FYM can provide 7.2 kg K_2O t^{-1} of available potassium, and it has been demonstrated that its concentration in soil can increase following the application of manures (Defra, 2018; Taiwo *et al.*, 2018). However, the application of muriate of potash fertiliser in November 2017 could have enhanced results.

The application of FYM to soil in Year 1 provided a source of readily available nitrogen. However, while the GM treatment did not receive N-fertiliser in 2017 it exhibited equivalent concentrations of %tN in October-2017. Both GM and SP started at the same %tN level, but the different inputs delivered similar results. The GM result was likely due to the low C:N stoichiometry of the cover crop mix (*Vicia sp*. and *R. sativus* foliage) that are quickly mineralised and subsequently release N (Ketterings et al., 2011; Creamer et al., 2016; Berthelin et al., 2022). This adds further evidence that legume use in cover crops, such as *Vicia sp*., could offset some short-term N-fertiliser requirements (Kaye et al., 2019).

The Olsen-P increase in the SP and FYM treatments of Experiment-1 sampled in May-October 2018 could have been stimulated by N-inputs, through the addition of N-fertiliser, of which the GM treatment only received in spring 2018 (Widdig et al., 2019; Chen et al., 2020).N-loadings stimulate the activity of soil phosphatase, which catalyses the hydrolysis of P, an effect which can be readily observed over the initial five-years in N-fertilised agri-soils (Widdig et al., 2019; Chen et al., 2020). Nutrient stoichiometry of N:P is critical for crop productivity and inputs affect N and P turnover (Chen et al., 2020; Dai et al., 2020). The temporal effect of %tN on Olsen-P, as in October 2017, with a lag period from N inputs, related to spatial variation. The experimental site was under N-fertilised rotations for over five years before both experiments were established which may have driven this effect.

While the impact on soil %tS was not immediately seen in this study and quite varied, this characteristic suggests that FYM (~2.4 kg SO_3 t^{-1}) could help reduce the use of SO_3 fertiliser (Defra, 2010). A study reported that microbial communities did not significantly vary across fields, but manures enhanced the activity of enzymes involved in nutrient cycling, including S-cycling, did differ contributing to bioweathering and mineralisation processes (Bowles et al., 2014; Min et al., 2019; Buckeridge et al., 2020; Finlay et al., 2020). FYM can be a source of S along with other essential nutrients and help reduce synthetic fertiliser inputs and balance crop requirements. However, regular soil tests should be conducted to avoid nutrient deficiencies or nutrient pollution because outcomes are influenced by soil inherent properties (Defra, 2018).

Crop Productivity

Experiment 2 had greater cover crops (*R. sativus* and *Vicia sp*. mix) aboveground biomass than in Experiment 1, likely caused by differences in soil properties. Brassicas, such as *Raphanus sativus,* establish more successfully on soils with pH 5.8–6.2 (AHDB, 2015), suggesting that pH 6.2 (±0.26 SD) encountered in Experiment-2 was in line with recommended values. Whereas pH of Experiment-1 was higher than the optimum range, pH 6.8 (±0.22-0.38 SD). Soil texture also impacts aboveground biomass, where lighter soils (< 20% clay) provide better structure for root development and may lead to greater foliage biomass (AHDB, 2015). This characteristic was met in Experiment-2, which soil was classified as loamy sand (0-15% clay) and sandy loam (0-20% clay) (FAO, 2020). In Experiment-1, four soil texture classes were identified and 45.2% of them were on heavier sandy clay loam (20-30% clay) (FAO, 2020). Other soil properties such as %tN influence crops' protein content too, where it was found to be lower in Experiment-2. The greater concentration of soil %tN in Experiment-1 resulted in higher N acquisition but not significantly greater aboveground biomass. Soil's inherent properties like texture resulted in different outcomes, and this is in accordance with Finney *et al.* (2016) who reported N acquisition was not correlated with biomass production.

The *T. aestivum* yields (spring wheat) in the FYM treatment were comparable to those in SP (1.2 t ha^{-1} ± 0.2 SD in both) which received N-fertiliser alone, but Experiment-1 overall yields were considerably lower than national average. Wheat yields in the UK in 2017 were on average 8.5 t ha^{-1} (Defra, 2017), The causes of reduced yields could not be ascertain but there was evidence of leaf scorching, which could have been caused by herbicide application of Ally Max SX (42 g ha^{-1}) and Duplosan (1 l ha^{-1}), and also due to signs of Take-all disease (Thomas, 1986; AHDB, 2010). These factors in combination with conversion to no-till could help explain. The weather conditions of 2018 had a negative effect on crop productivity nationally; ranging from snow cover and heavy rainfall in spring followed by a long hot and dry spell in summer (Defra, 2019). However, following 2017's poor production, yields recovered in 2018 to comparable *A. sativa* (winter oats) national levels (Defra, 2019). The average yield was 5.1 t ha^{-1} on both SP and FYM treatments, 5.4 t ha^{-1} in GM, and the UK average was 5.0 t ha^{-1} (Defra, 2019). The greater yields and respective grain protein in Experiment-2 GM treatment implies a response to cover crop residues. Crops utilise macronutrients, such as N, as building blocks for protein synthesis (Morgan and Connolly, 2013). Even though there were no significant treatment differences in soil %tN in autumn 2018, there could have been legacy effects from the N-fixing *Vicia sp*. residues that led to higher N availability and uptake (Kaye et al., 2019). However, the yield on this slope side were much lower than the UK average; SP = 2.1 t ha^{-1} and GM = 2.5 t ha^{-1} versus UK average = 5.0 t ha^{-1}.

Limitations of current study

This study was relatively short-term; one of the limits of field experiments is that data are often highly variable such that an unrealistic number of samples are likely required to have a high confidence of observing small effect sizes. Heterogeneity of soil within plots was shown to be a bigger factor for some results than treatment effects. This shows the importance of having data from multiple field sites and the weakness of extrapolating from single studies when computing predictive models that might combine data from short- and long-term studies that interject uncertainty.

4.6 Conclusion

In conclusion, this study showed that FYM and the *R. sativus* and *Vicia sp*. cover crop mix had an impact on soil chemical properties that are beneficial for crop growth, such as balanced pH, %tN, %S, and extractable K^+ and Mg^{2+}, but that response was influenced by spatial and temporal variation. No significant differences in wheat yields were observed with lower synthetic N-fertiliser inputs. However, yields were significantly lower than national average in the first year following conversion to no-till. The lower yields could be in response to conversation penalties or in combination with crop disease and/or scorching. The yields of winter oats obtained in year-2 were comparable to national levels in Experiment-1 but not in Experiment-2, showing once again temporal and spatial variation influence on outcomes.

This study suggests that C capture potential at a local level is affected by topography and soil properties influencing the rate of change in soil C using *in situ* direct measurements. It demonstrated that SOC concentration was affected by soil texture and not by the addition of organic amendments over a two-year field experiment. The results suggest that spatial heterogeneity in a four-hectare field, where soil types vary between sandy loam, sandy clay loam and loamy sand soils, can lead to different results depending on sampling location. This insight is critical when considering farm subsidies and C trading based on slowly changing measurements of SOC or SOM, which can vary due to the natural heterogeneities of a field and can be unrelated to management practices such as soil texture. Building soil C stocks and/or preventing further decline remains a target that should be aimed for.

Application of FYM and *R. sativus* and *Vicia sp*. cover crop mix did impact soil properties over a short period of time, such as its nutrient status. Furthermore, it confirmed that microbial biomass provides an early indication of changes in management practice where other properties, such as SOC or SOM, may take years to show a significant response to regular inputs.

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.

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 690142.

The authors would like to thank Mr Simon Allen for his agronomy work, Weaving Machinery for the leading of the drill, Mr Kevin Jones for his demonstration work on analytical techniques, and CERC for their machinery work during crop management field trials.

References

Abalos, D., Jeffery, S. Drury, C. F. and Wagner-Riddle, C. (2016) 'Improving fertilizer management in the U.S. and Canada for N2O mitigation: Understanding potential positive and negative side-effects on corn yields', Agriculture, Ecosystems and Environment. Elsevier B.V., 221, pp. 214–221. doi: 10.1016/j.agee.2016.01.044.

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R. M. and Smith, P. (2019) 'A critical review of the impacts of cover crops on nitrogen leaching , net greenhouse gas balance and crop productivity', *Global Change Biology*, 25, pp. 2530–2543. doi: 10.1111/gcb.14644.

Abram, M. (2020) 'How to accurately measure the organic carbon content of soil - Farmers Weekly', *Farmers Weekly*, 14 October.

AHDB (2010) 'Wheat and Barley disease managemente guide', *AHDB Cereales and Oilseeds*, pp. 219–256.

AHDB (2015) 'Using brassicas for Better Returns', *Beef and Sheep BRP Manual 6*.

Allison, R. (2015) *Many UK growers missing out on the benefits of zero tillage*, *Farmers Weekly*. Available at: https://www.fwi.co.uk/arable/many-uk-growers-missing-benefits-zero-tillage (Accessed: 14 June 2021).

Alskaf, K., Sparkes, D. L., Mooney, S. J., Sjögersten, S. and Wilson, P. (2020) 'The uptake of different tillage practices in England', *Soil Use and Management*, 36, pp. 27–44. doi: 10.1111/sum.12542.

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J.W., Mooney, S., van Wesemael, B. Wander, M. and Chabbi, A. (2020) 'Towards a global-scale soil climate mitigation strategy', *Nature Communications*. Springer US, 11:5427, pp. 1–10. doi: 10.1038/s41467-020-18887-7.

Amundson, R. and Biardeau, L. (2018) 'Soil carbon sequestration is an elusive climate mitigation tool', *PNAS*, 115(46), pp. 11652–11656. doi: 10.1073/pnas.1908917116.

Arneth, A., Barbosa, H., Benton, T., Calvin, K., Calvo, E., Connors, S., Cowie, A., Davin, E., Denton, F., van Diemen, R., Driouech, F., Elbehri, A., Evans, J., Ferrat, M., Harold, J., Haughey, E., Herrero, M., House, J., Howden, M., Hurlbert, M., Jia, G., Johansen, T. G., Krishnaswamy, J., Kurz, W., Lennard, C., Myeong, S., Mahmoud, N., Masson Delmotte, V., Mbow, C., McElwee, P., Mirzabaev, A., Morelli, A., Moufouma-Okia, W., Nedjraoui, D., Neogi, S., Nkem, J., de Noblet-Ducoudré, N., Olsson, L., Pathak, M., Petzold, J., Pichs-Madruga, R., Poloczanska, E., Popp, A., Pörtner, H.-O., Portugal Pereira, J., Pradhan, P., Reisinger, A., Roberts, D. C., Rosenzweig, C., Rounsevell, M., Shevliakova, E., Shukla, P., Skea, J., Slade, R., Smith, P., Sokona, Y., Sonwa, D. J., Soussana, J.-F., Tubiello, F., Verchot, L., Warner, K., Weyer, N., Wu, J., Yassaa, N., Zhai, P. and Zommers, Z. (2019) *Climate Change and Land - IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems: Summary for Policymakers*.

Arnold, P., Bardgett, R., Bradburne, R., Collins, C., Emmett, B., Evans, T., Field, R., Fitter, A., Goulding, K., Harris, J., Kerley, S., Mace, G., Macklin, R., McAuley, F., Mitchell, D., Morgan, G., Perkins, R., Quinton, J., Roos, F., Read, D., Smith, P., Wanzala-Ryan, C. and Willis, G. (2020) *Soil structure and its benefits: An evidence synthesis*. London.

Ayoubi, S., Mokhtari Karchegani, P., Mosaddeghi, M. R. and Honarjoo, N. (2012) 'Soil aggregation and organic carbon as affected by topography and land use change in western Iran', *Soil and Tillage Research*, 121, pp. 18–26. doi: 10.1016/j.still.2012.01.011.

Baveye, P. C., Schnee, L. S., Boivin, P., Laba, M. and Radulovich, R. (2020) 'Soil Organic Matter Research and Climate Change : Merely Re-storing Carbon Versus Restoring Soil Functions', *Frontiers in Environmental Science*, 8, pp. 1–8. doi: 10.3389/fenvs.2020.579904.

Berthelin, J. *et al.* (2022) 'Soil carbon sequestration for climate change mitigation: Mineralization kinetics of organic inputs as an overlooked limitation', *European Journal of Soil Science*, 73, pp. 1–9. doi: 10.1111/EJSS.13221.

Bowles, T. M., Acosta-Martínez, V., Calderón, F. and Jackson, L. E. (2014) 'Soil enzyme activities, microbial communities, and carbon and nitrogen availability in organic agroecosystems across an intensively-managed agricultural landscape', *Soil Biology and Biochemistry*, 68, pp. 252–262. doi: 10.1016/j.soilbio.2013.10.004.

Briedis, C., de Moraes Sá, J. C., Caires, E. F., Navarro, J. de F., Inagaki, T. M., Boer, A., Neto, C. Q., Ferreira, A. de O., Canalli, L. B. and dos Santos, J. B. (2012) 'Soil organic matter pools and carbon-protection mechanisms in aggregate classes influenced by surface liming in a no-till system', *Geoderma*, 170, pp. 80–88. doi: 10.1016/j.geoderma.2011.10.011.

Briones, M. J. I. and Schmidt, O. (2017) 'Conventional tillage decreases the abundance and biomass of earthworms and alters their community structure in a global meta-analysis', *Global Change Biology*, 23, pp. 4396–4419. doi: 10.1111/gcb.13744.

Brookes, P. (2001) 'The Soil Microbial Biomass: Concept, Measurement and Applications in Soil Ecosystem Research', *Microbes and Environment*, 16(3), pp. 131–140.

Buckeridge, K. M., Laba, M., Lemaire, G., Powlson, D., Tessier, D., Wander, M. and Baveye, P. C. (2020) 'Sticky dead microbes: Rapid abiotic retention of microbial necromass in soil', *Soil Biology and Biochemistry*, 149, p. 107929. doi: 10.1016/j.soilbio.2020.107929.

Bullock, J. M., Mccracken, M. E., Bowes, M. J., Chapman, R. E., Graves, A. R., Hinsley, S. A., Hutchins, M. G., Nowakowski, M., David, J., Nicholls, E., Oakley, S., Old, G. H., Ostle, N. J., Redhead, J. W., Woodcock, B. A., Bedwell, T., Mayes, S., Robinson, V. S., Pywell, R. F., Oxfordshire, W., House, M., Wittenham, L. and Ox, O.. (2021) ‘Does agri-environmental management enhance biodiversity and multiple ecosystem services?: A farm-scale experiment’, *Agriculture, Ecosystems and Environment*, 320, p. 107582. doi: 10.1016/j.agee.2021.107582.

Buysse, P., Roisin, C. and Aubinet, M. (2013) ‘Fifty years of contrasted residue management of an agricultural crop: Impacts on the soil carbon budget and on soil heterotrophic respiration’, *Agriculture, Ecosystems and Environment*, 167, pp. 52–59. doi: 10.1016/j.agee.2013.01.006.

CCC (2020) *Land use: Policies for a Net Zero UK Land use: Policies for a Net Zero UK*. London.

Cardoso, D. P., Silva, M. L. N., de Carvalho, G. J., de Freitas, D. A. F. and Avanzi, J. C. (2013) ‘Espécies de plantas de cobertura no recondicionamento químico e físico do solo’, *Agraria - Revista Brasileirade Ciencias Agrarias*, 8(3), pp. 375–382. doi: 10.5039/agraria.v8i3a2421.

Chen, J., van Groenigen, K. J., Hungate, B. A., Terrer, C., van Groenigen, J.-W., Maestre, F. T., Ying, S., Luo, Y., Jørgensen, U., Sinsabaugh, R. L., Olesen, J. E. and Elsgaard, L. (2020) ‘Long-term nitrogen loading alleviates phosphorus limitation in terrestrial ecosystems’, *Global Change Biology*. John Wiley & Sons, Ltd, 26, pp. 5077–5086. doi: 10.1111/gcb.15218.

COP21 (2015) *6th Sustainable Innovation Forum (SIF15) COP21 Paris*. Available at: http://www.cop21paris.org/ (Accessed: 3 December 2020).

Creamer, C. A., Jones, D. L., Baldock, J. A., Rui, Y., Murphy, D. V., Hoyle, F. C. and Farrell, M. (2016) ‘Is the fate of glucose-derived carbon more strongly driven by nutrient availability, soil texture, or microbial biomass size?’, *Soil Biology and Biochemistry*, 103, pp. 201–212. doi: 10.1016/j.soilbio.2016.08.025.

Dai, Z., Liu, G., Chen, H., Chen, C., Wang, J., Ai, S., Wei, D., Li, D., Ma, B., Tang, C., Brookes, P. C. and Xu, J. (2020) ‘Long-term nutrient inputs shift soil microbial functional profiles of phosphorus cycling in diverse agroecosystems’, *ISME Journal*, 14(3), pp. 757–770. doi: 10.1038/s41396-019-0567-9.

Defra (2010) ‘Fertiliser Manual’, p. 257. doi: RB209.

Defra (2017) *Farming Statistics Provisional crop areas, yields and livestock populations, United Kingdom*.

Defra (2018) *British Survey of Fertiliser Practice Fertiliser use on farm for the 2017 crop year*. London.

Defra (2019) *Farming Statistics Final Crop Areas, Yields, Livestock Populations and Agricultural Workforce, United Kingdom*.

Defra (2020) *The Path to Sustainable Farming: An Agricultural Transition Plan 2021 to 2024*.

Denef, K., Six, J. Merckx, R. and Paustian, K. (2002) ‘Short-term effects of biological and physical forces on aggregate formation in soils with different clay mineralogy’, *Plant and Soil*, 246, pp. 185–200. doi: 10.1023/a:1020668013524.

Eldor, P. A. (2016) ‘The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization’, *Soil Biology & Biochemistry*, 98, pp. 109–126.

Erkossa, T., Itanna, F., Stahr, K., Itanna, F., and Stahr, K. (2007) ‘Microbial Biomass Carbon as a Sensitive Indicator of Soil Quality Changes’, *Ethiopian Journal of Natural Resources*, 9(1), pp. 141–153.

Evans, D. L., Quinton, J. N., Davies, J. A. C., Zhao, J. and Govers, G. (2020) ‘Soil lifespans and how they can be extended by land use and management change’, *Environmental Research Letters*, 15(9), p. 0940b2. doi: 10.1088/1748-9326/aba2fd.

FAO (2020) ‘Soil Texture’. FAO Training, pp. 1–10.

Finlay, R. D., Mahmood, S., Rosenstock, N., Bolou-Bi, E. B., Köhler, S. J., Fahad, Z., Rosling, A., Wallander, H., Belyazid, S., Bishop, K. and Lian, B. (2020) ‘Reviews and syntheses: Biological weathering and its consequences at different spatial levels - From nanoscale to global scale’, *Biogeosciences*, 17(6), pp. 1507–1533. doi: 10.5194/bg-17-1507-2020.

Gan, H. Y., Schöning, I., Schall, P., Ammer, C. and Schrumpf, M. (2020) ‘Soil Organic Matter Mineralization as Driven by Nutrient Stoichiometry in Soils Under Differently Managed Forest Stands’, *Frontiers in Forests and Global Change*, 3, pp. 1–15. doi: 10.3389/ffgc.2020.00099.

Gewin, V. (2020) *Does Overselling Regenerative Ag’s Climate Benefits Undercut its Potential?*, *Civil Eats*. Available at: https://civileats.com/2020/10/01/does-overselling-regenerative-ags-climate-benefits-undercut-its-potential/ (Accessed: 6 October 2020).

Groffman, P. M., Hendrix, P. F. and Crossley, D. A. (1987) ‘Effects of a winter legume on phosphorus, potassium, calcium and magnesium cycling in a humid subtropical agroecosystem’, *Agriculture, Ecosystems and Environment*, 18(4), pp. 281–289. doi: 10.1016/0167-8809(87)90095-8.

Harrell Jr, F. E. (2022) ‘Hmisc’. cran.r-project.

Hernanz, J. L., Sánchez-Girón, V. and Navarrete, L. (2009) ‘Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions’, *Agriculture, Ecosystems and Environment*, 133, pp. 114–122. doi: 10.1016/j.agee.2009.05.009.

Heuck, C., Weig, A. and Spohn, M. (2015) ‘Soil microbial biomass C: N: P stoichiometry and microbial use of organic phosphorus’, *Soil Biology and Biochemistry*. Elsevier Ltd, 85, pp. 119–129. doi: 10.1016/j.soilbio.2015.02.029.

Janzen, H. H. (2006) ‘The soil carbon dilemma: Shall we hoard it or use it?’, *Soil Biology &*

Biochemistry, 38, pp. 419–424. doi: 10.1016/j.soilbio.2005.10.008.

Jenkinson, D. S., Brookes, P. C. and Powlson, D. S. (2004) 'Measuring soil microbial biomass', *Soil Biology & Biochemistry*, 36, pp. 5–7. doi: 10.1016/j.soilbio.2003.10.002.

Kallenbach, C. M., Frey, S. D. and Grandy, A. S. (2016) 'Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls', *Nature Communications*. Nature Publishing Group, 7(13630), pp. 1–10. doi: 10.1038/ncomms13630.

Kassambara, A. (2020) 'ggpubr: "ggplot2" Based Publication Ready Plots'. R package version 0.4.0.

Kassambara, A. (2021) 'rstatix: Pipe-Friendly Framework for Basic Statistical Tests'. R package version 0.7.0.

Kaye, J., Finney, D., White, C., Bradley, B., Schipanski, M., Alonso-Ayuso, M., Hunter, M., Burgess, M. and Mejia, C. (2019) 'Managing nitrogen through cover crop species selection in the U.S. Mid-Atlantic', *PLoS ONE*, 14(4), p. e0215448. doi: 10.1371/journal.pone.0215448.

Ketterings, Q. M., Kingston, J., McIlvennie, S., Godwin, G., Gami, S., Stanyard, M. and Czymmek, K. (2011) 'What 's Cropping Up?', *New York Field Crops & Soils*, pp. 1–4.

Krebs, C. J. (2014) 'Sampling Designs - Random Sampling, Adaptive and Systematic Sampling', in *Ecological Methodology*. 3rd edn, pp. 324–379.

Lal, R. (1997) 'Degradation and resilience of soils', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 352, pp. 997–1010. doi: 10.1098/rstb.1997.0078.

Lal, R. (2016) 'Soil health and carbon management', *Food and Energy Security*, 5(4), pp. 212–222. doi: 10.1002/fes3.96.

Lehmann, J. and Kleber, M. (2015) 'The contentious nature of soil organic matter', Nature, 528(16069), pp. 60–68. doi: 10.1038/nature16069.

Liang, Z., Cao, B., Jiao, Y., Liu, C., Li, X., Meng, X., Shi, J. and Tian, X. (2022) 'Effect of the combined addition of mineral nitrogen and crop residue on soil respiration, organic carbon sequestration, and exogenous nitrogen in stable organic matter', *Applied Soil Ecology*, 171, p. 104324. doi: 10.1016/j.apsoil.2021.104324.

Lin, Y., Ye, G., Kuzyakov, Y., Liu, D., Fan, J. and Ding, W. (2019) 'Long-term manure application increases soil organic matter and aggregation, and alters microbial community structure and keystone taxa', *Soil Biology and Biochemistry*. Elsevier, 134(March), pp. 187–196. doi: 10.1016/j.soilbio.2019.03.030.

Lines-Kelly, R. (1992) *Plant nutrients in the soil*, *DPI*. Available at: https://www.dpi.nsw.gov.au/agriculture/soils/improvement/plant-nutrients (Accessed: 7 September 2021).

Liu, M., Qiao, N., Xu, X., Fang, H., Wang, H. and Kuzyakov, Y. (2020) 'C:N stoichiometry of stable and labile organic compounds determine priming patterns', *Geoderma*, 362, p.

114122. doi: 10.1016/j.geoderma.2019.114122.

Lupwayi, N. Z., Clayton, G. W., O'Donovan, J. T., Harker, K.N., Turkington, T.K. and Rice, W. A. (2004) ‘Decomposition of crop residues under conventional and zero tillage’, *Canadian Journal of Soil Science*, 84, pp. 403–410. doi: 10.1016/j.still.2007.01.007.

Makowski, D., Wiernik, B. M., Patil, I., Lüdecke, D., Ben-Shachar, M. S., White, M. and Rabe, M. M. (2022) ‘correlation’. cran.r-project.

Mangiafico, S. (2021) ‘rcompanion: Functions to Support Extension Education Program Evaluation’. R package version 2.4.1.

Mary, B., Clivot, H., Blaszczyk, N., Labreuche, J. and Ferchaud, F. (2020) ‘Soil carbon storage and mineralization rates are affected by carbon inputs rather than physical disturbance: Evidence from a 47-year tillage experiment’, *Agriculture, Ecosystems and Environment*, 299, p. 106972. doi: 10.1016/j.agee.2020.106972.

Meurer, K. H. E., Haddaway, N. R., Bolinder, Martin A. and Kätterer, T. (2018) ‘Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach’, *Earth-Science Reviews*. Elsevier, 177, pp. 613–622. doi: 10.1016/j.earscirev.2017.12.015.

Min, K., Buckeridge, K., Ziegler, S. E., Edwards, K. A., Bagchi, S., Billings, S. A., Kate, B., Ziegler, S. E., Edwards, K. A., Bagchi, S. and Billings, S. A. (2019) ‘Temperature sensitivity of biomass-specific microbial exo-enzyme activities and CO2 efflux is resistant to change across short- and long-term timescales’, *Global Change Biology*, 25, pp. 1793–1807. doi: 10.1111/gcb.14605.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, Bhabani S., Field, D J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, P., Martin, M., McConkey, B. G., Mulder, V. L, O'Rourke, S., Richer-de-Forges, A. C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C-C., Vågen, T-G., van Wesemael, B. and Winowiecki, L. (2017) ‘Soil carbon 4 per mille’, *Geoderma*, 292, pp. 59–86. doi: 10.1016/j.geoderma.2017.01.002.

Morgan, J. B. and Connolly, E. L. (2013) ‘Plant-Soil Interactions: Nutrient Uptake’, *Nature Education Knowledge*, 4(8), p. 2.

Mulvaney, M. J. and Devkota, P. (2020) ‘Adjusting Crop Yield to a Standard Moisture Content’, *Edis*, SS-AGR-443, p. 5. doi: 10.32473/edis-ag442-2020.

Mutegi, J. K., Petersen, B. M., Munkholm, L. J. and Hansen, E. M. (2011) ‘Belowground carbon input and translocation potential of fodder radish cover-crop’, *Plant and Soil*, 344, pp. 159–175. doi: 10.1007/s11104-011-0737-7.

National Statistics. (2019). *The British survey of fertiliser practice: fertiliser use on farm crops for crop year 2018*, Defra, p. 117.

NFU (2019) *Achieving Net Zero - Farming's 2040 Goal*. Stoneleigh.

No-Till.UK (2020) *Welcome to No-Till.uk*. Available at: http://www.no-till.uk/ (Accessed: 4 December 2020).

Orgiazzi, A., Singh, B., Wall, D., Barrios, E., Kandeler, E., Moreira, F., de Deyn, G., Chotte, J.-L., Six, J., Hedlund, K., Briones, M., Miko, L., Johnson, N., Ramirez, K., Fierer, N., Kaneko, N., Lavelle, P., Eggleton, P., Lemanceau, P., Bardgett, R., Jeffery, S., Fraser, T., Behan Pelletier, V., van der Putten, Wim., Montanarella, L. and Jones, A. (eds) (2016) *Global Soil Biodiversity Atlas*. Luxembourg: European Commission, Publications Office of the European Union. doi: doi:10.2788/799182.

Pittelkow, C. M., Liang, X., Linquist, B. A., van Groenigen, L. J., Lee, J., Lundy, M. E., van Gestel, N., Six, J., Venterea, R. T. and van Kessel, C. (2015) 'Productivity limits and potentials of the principles of conservation agriculture', Nature, 517(7534), pp. 365–368. doi: 10.1038/nature13809.

Powlson, D. S., Prookes, P. C. and Christensen, B. T. (1987) 'Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation', *Soil Biology and Biochemistry*, 19(2), pp. 159–164. doi: 10.1016/0038-0717(87)90076-9.

Powlson, D. S., Whitmore, A. P. and Goulding, K. W. T. (2011) 'Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false', *European Journal of Soil Science*, 62(1), pp. 42–55. doi: 10.1111/j.1365-2389.2010.01342.x.

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A. and Cassman, K. G.. (2014) 'Limited potential of no-till agriculture for climate change mitigation', *Nature Climate Change*, 4(8), pp. 678–683. doi: 10.1038/nclimate2292.

Pribyl, D.W. (2010) 'A critical review of the conventional SOC to SOM conversion factor', *Geoderma*, 156(3–4), pp. 75–83. Available at: https://doi.org/10.1016/j.geoderma.2010.02.003.

R Core Team (2021) 'R: A Language and Environment for Statistical Computing'. Vienna, Austria: R Foundation for Statistical Computing.

Rand Corporation (1955) *A Million Random Digits with 100,000 Normal Deviates*. New York: The Free Press.

Revelle, W. (2022) 'psych_2.2.5.tar.gz'.

Roesch-Mcnally, G. E., Basche, A. D., Arbuckle, J. G., Tyndall, J. C., Miguez, F. E., Bowman, T. and Clay, R. (2018) 'The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption', *Renewable Agriculture and Food Systems*, 33(4), pp. 322–333. doi: 10.1017/S1742170517000096.

Rowell, D. L. (1994) *Soil Science: Methods and Applications*. Harlow, Essex: Pearson Education Ltd.

Rowley, M. C., Grand, S. and Verrecchia, É. P. (2018) ‘Calcium-mediated stabilisation of soil organic carbon’, *Biogeochemistry*. Springer International Publishing, 137, pp. 27–49. doi: 10.1007/s10533-017-0410-1.

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D. A.C., Nannipieri, P., Rasse, D. P., Thomas, P. E. L. (1986) ‘Evaluation of the effects of scorching caused by the directed application of a paraquat-containing herbicide mixture to the base of maize plants at various ages’, *South African Journal of Plant and Soil*, 3(1), pp. 18–20. doi: 10.1080/02571862.1986.10634179.

Schrumpf, M., Kaiser, K., Guggenberger, G., Persson, T., Kögel-Knabner, I. and Schulze, E. D. (2013) ‘Storage and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals’, *Biogeosciences*, 10, pp. 1675–1691. doi: 10.5194/bg-10-1675-2013.

Schweizer, S. A., Mueller, C. W., Höschen, C., Ivanov, P. and Kögel-Knabner, I. (2021) ‘The role of clay content and mineral surface area for soil organic carbon storage in an arable toposequence’, *Biogeochemistry*, 3, pp. 1–20. doi: 10.1007/s10533-021-00850-3.

Science 20 (2018) ‘Food and Nutrition Security: Improving Soils and Increasing Productivity’. Argentina, p. 6.

Searchinger, T., Waite, R., Hanson, C. and Ranganathan, J. (2019) *Creating a Sustainable Food Future: A menu of Solutions to Feed Nearly 10 Billion People by 2050*, *World Resources Report*. Edited by E. Matthews. Washington, D.C.

Silgram, M. and Harrison, R. (1998) *The Mineralisation of Nitrogen in Cover Crops : A Review*.

Six, J., Bossuyt, H., Degryze, S. and Denef, K. (2004) ‘A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics’, *Soil & Tillage Research*, 79, pp. 7–31. doi: 10.1016/j.still.2004.03.008.

Six, J. and Jastrow, J. D. (2002) ‘Organic matter turnover’, in Lal, R. (ed.) *Encyclopedia of Soil Science*. New York: Marcel Dekker, Inc, pp. 936–942.

Sparks, D. L. (ed.) (2015) *Advances in Agronomy*. 1st ed., *Journal of Chemical Information and Modeling*. Oxford: Academic Press. doi: 10.1017/CBO9781107415324.004.

Storr, T., Simmons, R. W. and Hannam, J. A. (2019) ‘A UK survey of the use and management of cover crops’, *Annals of Applied Biology*. Blackwell Publishing Ltd, 174(2), pp. 179–189. doi: 10.1111/aab.12488.

Tan, K. H. (2005) *Soil sampling, preparation and analysis*. 2nd edn. New York: CRC Press.

Taiwo, A. A., Adetunji, M. T., Azeez, J. O. and Elemo, K. O. (2018) ‘Kinetics of potassium release and fixation in some soils of Ogun State, Southwestern, Nigeria as influenced by organic manure’, *International Journal of Recycling of Organic Waste in Agriculture*, 7, pp.

251–259. doi: 10.1007/s40093-018-0211-0.

Thomas, P. E. L. (1986) ‘Evaluation of the effects of scorching caused by the directed application of a paraquat-containing herbicide mixture to the base of maize plants at various ages’, *South African Journal of Plant and Soil*, 3(1), pp. 18–20. doi: 10.1080/02571862.1986.10634179.

Tomé, D., Cordella, C., Dib, O. and Péron, C. (2019) *Nitrogen and protein content measurement and nitrogen to protein conversion factors for dairy and soy protein-based foods: a systematic review and modelling analysis*, *FAO/WHO*. Edited by H. Cadman. doi: 10.2307/1232585.

Tsiafouli, M. M. A., Thebault, E., Sgardelis, S. P., de Ruiter, P. C., van der Putten, W. H., Birkhofer, K., Hemerik, L., de Vries, F. T., Bardgett, R. D., Brady, M. V., Bjornlund, L., Jorgensen, H. B., Christensen, S., Hertefeldt, T. D., Hotes, S., Gera Hol, W. H., Frouz, J., Liiri, M., Mortimer, S. R., Setala, H., Tzanopoulos, J., Uteseny, K., Pizl, V., Stary, J., Wolters, V. and Hedlund, K. (2015) ‘Intensive agriculture reduces soil biodiversity across Europe’, *Global Change Biology*, 21, pp. 973–985. doi: 10.1111/gcb.12752.

USDA-NRCS (2011) ‘Carbon to Nitrogen Ratios in Cropping Systems’, *USDA Natural Resources Conservation Service*. USDA Natural Resources Conservation Service, p. 2.

Valboa, G., Lagomarsino, A., Brandi, G., Agnelli, A. E., Simoncini, S., Papini, R., Vignozzi, N. and Pellegrini, S. (2015) ‘Long-term variations in soil organic matter under different tillage intensities’, *Soil and Tillage Research*, 154, pp. 126–135. doi: 10.1016/j.still.2015.06.017.

Vance, E. D., Brookes, P. C. and Jenkinson, D. S. (1987) ‘An extraction method for measuring soil microbial biomass C’, *Soil Biology & Biochemistry*, 19(6), pp. 703–707. doi: 10.1016/0038-0717(87)90052-6.

Virto, I., Barré, P., Burlot, A. and Chenu, C. (2012) ‘Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems’, *Biogeochemistry*, 108, pp. 17–26. doi: 10.1007/s10533-011-9600-4.

Wang, Z., Hassan, M. U., Nadeem, F., Wu, L., Zhang, F. and Li, X. (2020) ‘Magnesium Fertilization Improves Crop Yield in Most Production Systems: A Meta-Analysis’, *Frontiers in Plant Science*, 10, pp. 1–10. doi: 10.3389/fpls.2019.01727.

Wang, F., Che, R., Deng, Y., Wu, Y., Tang, L., Xu, Z., Wang, W., Liu, H. and Cui, X. (2021) ‘Air-drying and long time preservation of soil do not significantly impact microbial community composition and structure’, *Soil Biology and Biochemistry*, 157, p. 108238. doi: 10.1016/j.soilbio.2021.108238.

Watts, C. W., Clark, L. J., Poulton, P. R., Powlson, D. S. and Whitmore, A. P. (2006) ‘The role of clay, organic carbon and long-term management on mouldboard plough draught measured on the Broadbalk wheat experiment at Rothamsted’, *Soil Use and Management*, 22, pp. 334–341. doi: 10.1111/J.1475-2743.2006.00054.X.

Wendling, M., Büchi, L., Amossé, C., Sinaj, S., Walter, A. and Charles, R. (2016) 'Influence of root and leaf traits on the uptake of nutrients in cover crops', *Plant and Soil*, 409, pp. 419–434. doi: 10.1007/s11104-016-2974-2.

Wei, T., Simko, V., Levy, M., Xie, Y., Jin, Y., Zemla, J., Freidank, M., Cai, J. and Protivinsky, T. (2021) 'corrplot_0.92.tar.gz'. cran.r-project.

Wickham, H. *et al.* (2019) 'Welcome to the tidyverse', *Journal of Open Source Software*, 4(43), p. 1686. doi: 10.21105/joss.01686.

Widdig, M., Schleuss, P., Weig, A. R., Guhr, A., Biederman, L. A., Borer, E. T., Crawley, M. J., Kirkman, K. P., Seabloom, E. W., Wragg, P. D. and Spohn, M. (2019) 'Nitrogen and Phosphorus Additions Alter the Abundance of Phosphorus-Solubilizing Bacteria and Phosphatase Activity in Grassland Soils', *Frontiers in Environmental Science*, 7(185), pp. 1–15. doi: 10.3389/fenvs.2019.00185.

Yao, Y., Dai, Q., Gao, R., Gan, Y. and Yi, X. (2021) 'Effects of rainfall intensity on runoff and nutrient loss of gently sloping farmland in a karst area of SW China', *PLoS ONE*, 16(3), p. e0246505. doi: 10.1371/journal.pone.0246505.

Xiong, X., Grunwald, S., Myers, D. B., Kim, J., Harris, W. G. and Bliznyuk, N. (2015) 'Assessing uncertainty in soil organic carbon modeling across a highly heterogeneous landscape', *Geoderma*, 251–252, pp. 105–116. doi: 10.1016/j.geoderma.2015.03.028.

Zamanian, K., Zhou, J. and Kuzyakov, Y. (2021) 'Soil carbonates: The unaccounted, irrecoverable carbon source', *Geoderma*, 384, p. 114817. doi: 10.1016/j.geoderma.2020.114817.

Zuber, S. M. and Villamil, M. B. (2016) 'Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities', *Soil Biology and Biochemistry*, 97, pp. 176–187. doi: 10.1016/j.soilbio.2016.03.011.