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Modern arable and diverse ley farming systems can increase soil organic matter faster than global targets

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Abstract

Agriculture can be pivotal in mitigating climate change through soil carbon sequestration. Land conversion to pasture has been identified as the most effective method to achieve this. Yet, it creates a perceived trade-off between increasing soil carbon and maintaining arable food crop production. In this on-farm study, we assessed the potential of incorporating a 2-year diverse ley (consisting of 23 species of legumes, herbs, and grasses) within a 7-year arable crop rotation for soil organic matter accumulation. We established upper and lower boundaries of soil organic matter accumulation by comparing this approach to positive (permanent ley, akin to conversion to permanent pasture) and negative (bare soil) references. Our findings in the 2-year diverse ley treatment show greater soil organic matter accumulation in plots with lower baseline levels, suggesting a potential plateau of carbon sequestration under this management practice. In contrast, the positive reference consistently showed a steady rate of organic matter accumulation regardless of baseline levels. Moreover, we observed a concurrent increase in labile carbon content in the 2-year ley treatment and positive reference, indicating improved soil nutrient cycling and ecological processes that facilitate soil carbon sequestration. Our results demonstrate that incorporating a 2-year diverse ley within arable rotations surpasses the COP21 global target of a 0.4% annual increase in soil organic carbon. These findings, derived from a working farm's practical and economic constraints, provide compelling evidence that productive arable agriculture can contribute to climate change mitigation efforts.

Introduction

Soil stocks have been degraded worldwide (Lal and Stewart, 1992), and to date, approximately 116 Pg of soil carbon (C) has been released into the atmosphere globally (Sanderman, Hengl, and Fiske, 2017). Land use change and unsustainable farming practices have led to soil erosion (Montgomery, 2007), negative impacts on aboveground biodiversity (Gilroy et al., 2008), and the gradual degradation of the global soil resource. Carbon capture is, therefore, a crucial concept in mitigating climate change as it helps reduce the concentration of atmospheric greenhouse gases caused by human activities (Fawzy et al., 2020). Organic matter accumulation in agricultural soils is a relatively low-cost technique for capturing carbon, providing multiple additional benefits (Bossio et al., 2020). Crop rotations that increase soil organic matter (SOM) have been associated with enhanced below-ground and aboveground biodiversity (McDaniel, Tiemann, and Grandy, 2014), improved crop productivity (Lange et al., 2015), and increased resilience to floods and droughts (Falkenmark and Rockström, 2008). Carbon capture in agricultural soils thus serves as a climate change mitigation and adaptation strategy.

A healthy soil is characterized by high or increasing SOM (Loveland, 2003); the benefits of healthy soils for crop production and society have been known for some time (Acton and Gregorich, 1995). Soil health is commonly defined as the ongoing ability of soil to function as a vital living ecosystem that supports plants, animals, and humans (Lehmann et al., 2020). Healthy soils exhibit favorable characteristics such as soil structure and aeration, nutrient cycling and provision, prevention of salinization, suppression of soil-borne plant pathogens, and a diverse population of soil flora and fauna—all of which support crop growth (Janvier et al., 2007; Senechkin, van Overbeek, and van Bruggen, 2014; van Bruggen, 2015). SOM is a key soil component that underpins these functions (Lehmann et al., 2020); its management in agricultural soils is a dynamic process that requires a continuous input of fresh organic material (Montgomery, 2007). Understanding the direction and rate of SOM change is critical for addressing soil degradation issues (Loveland, 2003) and should be at the forefront of our efforts to combat climate change (Montanarella and Panagos, 2021).

The success of carbon capture in SOM within productive systems depends on the achievable carbon accumulation rate and the soil's capacity to store carbon. The global potential for carbon storage in soil is estimated to be between 114 and 242 Pg C (Lal et al., 2018), which is equivalent to more than a decade of current human carbon emissions (Amundson and Biardeau, 2018). The management practices employed in agricultural land systems influence both the mechanisms controlling the rate of SOM accumulation and the degree of saturation (Six et al., 2002). However, a major challenge in implementing soil regeneration interventions is the time required for the benefits to materialize, often remaining below the detection threshold for a considerable period (Machmuller et al., 2015). Further, introducing techniques that promote the buildup of SOM in annual cropping systems poses a challenge for land managers as they typically disrupt business-as-usual (Minasny et al., 2017). For instance, attempts to reduce or eliminate tillage have been made but with limited success (Blanco-Canqui and Wortmann, 2020).

Switching from annual cropping to long-term pastures through land use change is known to facilitate SOM accumulation (Machmuller et al., 2015), but there is a growing demand for annual crops such as vegetables, pulses, and cereals (Tilman et al., 2011). Integrating short-term leys as part of arable crop rotations could provide some benefits similar to perennial crops (Poulton et al., 2018), while still meeting the demand for annual crops. The primary purpose of these leys is soil protection and improvement, but they can also contribute directly to profitability and stabilize farm income through diversification (Harkness et al., 2021). The impact of leys on soil health and crop yields can be enhanced by plant species diversity (Lange et al., 2015). Highly diverse leys develop deeper root systems than expected from their monoculture traits, accessing a greater soil resource that can correlate with aboveground productivity (Mueller et al., 2013). The strategic use of fertility-building leys can significantly reduce dependence on imported nutrients, which poses potential risks beyond the control of the farmer and is subject to trade and market fluctuations, as exemplified by recent global events.

This study explores the use of plant biomass, primarily created by a diverse ley of 23 species, to drive soil function regeneration through SOM accumulation—within a working farm context. We measured the change in SOM across four fields on an organic farm from 2014 to 2019, using a space-for-time arrangement to capture the 7-year rotation practiced on the farm. Each field was started at a different point of the rotation to cover all transitions as the experiment stretched for 5 years only. We compared the effects of retaining crop residues (enhanced treatment) to their removal (standard treatment) in a diverse ley rotation featuring a 2-year ley phase, to a 5-year ley (positive reference akin to permanent pasture), and to a routinely tilled fallow treatment (negative reference with zero fresh carbon). All treatments in this study reflect practical interventions commonly employed by farmers, which is a significant advantage. The study is conducted within the constraints of an economically viable working system. We utilize an existing crop rotation to investigate the influence of different levels of organic matter inputs on soil health. Our primary hypothesis is that an increase in the quantity of plant biomass retained within the system will lead to a gradual augmentation of SOM over time.

Materials and methods

Site description

The experiment was conducted at Yatesbury Farm in South England (51°26′32.68″ N, 1°54′08.57″ W). The geology is lower gray chalk, and the upper soil texture is silty clay loam (Blewbury and Yatesbury soil series) (Findlay and Colborne, 1984). Most of the land has less than 1° incline, daily average temperature ranges from −2 to 24°C (2016–2019), mean annual rainfall is 662.25 mm (2016–2019, weather data supplied by Iteris). The farm comprises 550 hectares of cropping, pasture and woodland, and a 280-head suckler herd. Organic conversion began in 1998, having previously been farmed in intensive arable production in the 1990s, the farm is also managed biodynamically (Birkhofer et al., 2008; Mader et al., 2002). The farm has not been ploughed since 2003, so light/reduced tillage to approximately 75 mm depth is used instead.

Experimental design

Four fields were chosen in 2014 to represent the rotation typical for the farm on a space-for-time substitution basis (Pickett, 1989) and to best represent the soil and weed diversity across the farm. The fields had a research area 80 m × 78 m demarcated away from field margins, each comprising three replicate blocks of experimental plots (Fig. 1). Each replicate block contained four treatment plots, where the treatments described in Table 1 were applied continuously. Cattle were excluded from research areas.

All treatments were randomly allocated to individual plots within a block, and reference treatments were allocated half-size plots as no crop measurements were carried out between 2014 and 2019. The standard treatment represents the business-as-usual scenario in this region, where crop residues such as cereal straw are bailed and sold off-farm for animal bedding. The enhanced treatment represents in-field retention of crop residues or winter cover crops. The crop and management within each field are shown in Table 2. Weather, commodity market, weed burden, and changing fertility encouraged variations to crop interventions throughout the experiment according to common farming practice. For example, crop varieties, time of sowing, a switch from winter to spring crop, or extra cultivations due to weed pressure were applied. Crop management in the enhanced plots focused on adding as much biomass to the soil from *in situ* plant growth as possible. The biomass quality varied according to the crop grown and the season and was not measured. A diverse mixture of 23 ley species was used to maximize the performance of the key ley phase (see Supplementary material for the full list; Döring et al., 2013).

Field sampling protocols and laboratory analysis

The location of plot sampling sites was determined using a stratified random approach by splitting each full-size plot into quarters, using the soil core location described below or randomly generating coordinates for one sampling site per quarter. This resulted in four sampling sites per full-size plot (two sampling sites per reference plots), 36 per field, and 144 across all four fields of the experiment.

Soil baseline cores were taken in autumn 2014, and the samples were taken at 0.5 m from the start of each quarter plot and along the center line of the plots (Fig. 1). The cores, 80 mm in diameter, were taken at 0–100 and 100–300 mm depth and stored at −20°C until analysis. A second set of soil cores was taken in autumn 2019 according to the same sampling design, 2 m from the start of the quarter plots. In November 2019, the 2014 cores were defrosted, and all cores were analyzed by NRM laboratories (Bracknell, UK) for SOM and labile carbon. SOM was analyzed

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Figure 1. Left to right; aerial map of experimental field locations (orange squares); drone image of croft field showing plots within the field setting; and drone image of the layout of three replicate blocks of four treatment plots (full-size-plots: size 8 m × 80 m). Treatments: negative reference (1); positive reference (2); standard (3); enhanced (4). The two reference treatments share one full-size plot.

using loss on ignition (LOI) (NRM, 2019). These samples were first air-dried at a temperature not greater than 30°C and sieved to 2 mm, the organic matter was then destroyed by dry combustion at 430°C, and the loss in weight of the sample is reported in g kg^{-1} of the original sample as the organic matter content. Soil organic carbon (SOC) was not directly measured in this experiment; we used 0.58 to convert SOM to SOC (Pribyl, 2010). We report the relative change in SOM over time only; bypassing potential inaccuracy (Roper et al., 2019) as the same error is likely to occur in both estimates. Labile carbon was assessed by reacting potassium permanganate ($KMnO_4$) solution with soil samples and determined by spectroscopy (Weil et al., 2003).

Bulk density samples were taken in September 2018 at 5 m start point following the center line approach outlined above, using a spade and digging a hole to a depth of 500 mm with enough clearance to hammer in the cylinder horizontally. Bulk density samples were taken using the metal ring of a known volume at three depths: 0–100, 100–300, and 300–500 mm using the USDA standard bulk density protocol (USDA, 2020).

Water infiltration rates were assessed by filling a 150 mm diameter tube with water. The tube was driven 7.5 cm into the soil, 444 ml of water (equivalent to 25 mm of precipitation) were added to simulate field capacity, then a second batch was added, and the time for the water to percolate into the soil was measured. We did not measure soil moisture prior to this addition of water and, therefore, may not have achieved field capacity with the first addition.

Manual penetrometer (Utset and Cid, 2001) readings were taken at randomly determined points within each plot by pushing the penetrometer into the soil uniformly and recording the point pressure at each depth at a range of 100–700 mm. The penetrometer sizes were probe length: 75 cm, probe diameter: 12 mm, and tip diameter: 13 mm. All soil compaction measurements were taken in years 2017, 2018, and 2019.

Table 1. Experimental treatments

Name	Treatment
Positive reference treatment	Continuous diverse ley representing max carbon input with retention of all crops residues in-field
Enhanced input	In-field retention of crop residues and cultivation of winter cover crops
Standard input	Aboveground crop residues are removed
Negative reference treatment	No crop, routine tillage 3 times yr^{-1}: spring, summer, and autumn, to restrict plant growth

As replicated throughout the experiment, enhanced and standard represent normal crop rotation, positive and negative reference indicate system boundary treatments.

Statistical analysis

Data were recorded and validated for completeness, and changes in SOM from 2014 to 2019 were calculated as a derived variable (SOM2019-SOM2014). Measurements taken at four sampling sites within the enhanced and standard treatments and at two sampling sites in each reference treatment were analyzed using a nested mixed model with treatment plot nested in replicate and replicate nested in the field (1|field/replicate/treatment plot). Field, replicate, and treatment plot terms were treated as random effects. Mixed models were used to analyze all the responses, with a support distribution as required by each outcome (normal or lognormal).

The 2014 baseline observations of SOM and labile carbon were compared with the 2019 data to assess the change. A Summary Statistics Approach for the years of repeated measures was used. A normal distribution was used to model SOM change; adding baseline covariates to the model was attempted but did not improve model performance, a lognormal distribution could not be used as some values were negative. A normal distribution was used to model labile carbon in 2014 and 2019. Labile carbon varies with season and year depending upon growing conditions (Kirschbaum, 2013; Jiang et al., 2006), so no direct comparison between 2014 and 2019 was made. Slopes of linear regression fits were compared by extra sum-of-squares *F* test. A normal distribution was used to model bulk density by treatment. A lognormal distribution was used to model infiltration by crop and treatment due to large, tailed data. A normal distribution was used to model penetrometer readings at 100 and 200 m depth. Some statistically significant results may be of such small effect that they are of no practical importance; these are noted when interpreting the results. The data were analyzed and modelled in R, version 3.6.3. The denominator degrees of freedom were computed by the Kenward–Roger method in all cases. *P*-values less than 0.05 are deemed indicative of statistically significant effects.

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Table 2. Crop rotation and the position of individual fields within the 7-year rotation at the beginning of the experiment in 2014

Rotation year	Rotation crop	Field in 2014	Standard biomass-input treatment	Enhanced biomass-input treatment
1	Diverse ley	Long barrow	Mowed for hay/silage	Topped after 15th June to promote lignin production and reduce weed seed set
2	Diverse ley		Grazed	Grazed
3	Cereal spelt or wheat or oats	Hut field	Remove straw	Chop and incorporate straw
4	Cereal spelt or oats		Remove straw	Chop and incorporate straw
5	Bean whole crop silage	Fifty acres	Harvested as forage silage	Cut and mulched as green manure nothing harvested
6	Spring beans		Fallow over winter	Green cover over winter
7	Spring oats under sown with diverse ley	Croft field	Harvest as whole crop	Chop and spread straw and green material

Two right-hand columns indicate main crop management interventions during each year of rotation.

Results

Effects of treatment

Between 2014 and 2019, SOM changed over 5 years in this experiment at 0–100 and 100–300 mm depths (both $P < 0.001$). The largest change in SOM occurred in the positive reference (5-year ley), with an increase of 8.2 g kg^{-1} SOM over 5 years (CI 6.0–10.5, $P < 0.001$) at 0–100 mm depth and 3.0 g kg^{-1} SOM (CI 0.7–5.2, $P = 0.013$) at the 100–300 mm depth. Both the enhanced and standard treatments increased SOM at the 0–100 mm depth (3.7 g kg^{-1} [CI 1.7–5.6, $P < 0.001$] and 2.8 g kg^{-1} [Cl 0.9–4.8, $P = 0.008$], respectively). The enhanced treatment was not different to the standard treatment at either depth (Fig. 2).

Compared to the negative reference, labile carbon in 2019 was greater under all other biomass treatments at the 0–100 mm depth (positive reference, enhanced, and standard). There was no difference between the positive reference, standard, and enhanced treatments (Fig. 3). Regarding soil bulk density, there was no difference between the standard and enhanced treatments, nor did we find a correlation between SOM and bulk density ($P = 0.59$). We did not observe significant effects of treatment on either penetrometer readings or water infiltration rate (Supplementary data).

Effects of time

A comparison of SOM content between 2014 and 2019 in Figure 4 shows the changes in the rate of SOM accumulation over time. Overall, SOM was higher in 2019 compared to 2014 ($P = 0.024$). Within the observed range, the positive and negative reference treatments added carbon at a constant rate (Fig. 4 inset),

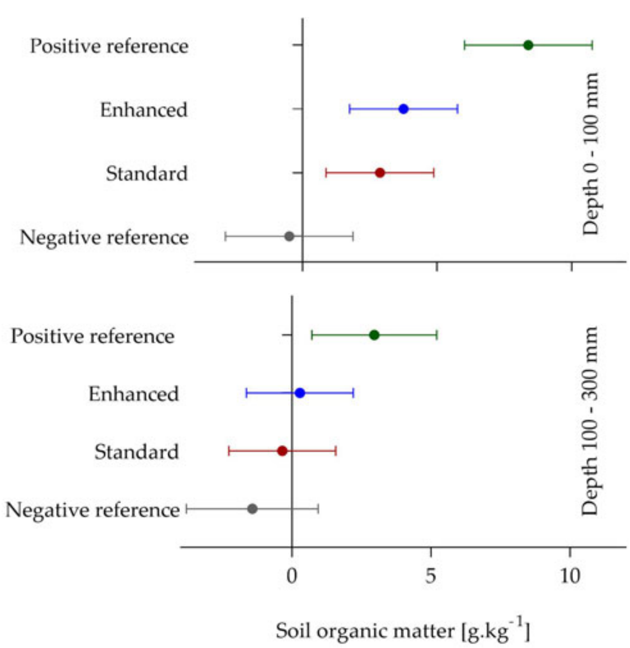

Figure 2. Change in SOM between 2014 and 2019 (g kg^{-1}) in four plant biomass treatments: enhanced (retention of all crop residue *in situ*), standard (removal of residues, business as usual), positive reference (5-year ley), and negative reference (no plants). Dots show predicted means by treatments and depth. Bars represent 95% confidence intervals (also see Supplementary Table S1).

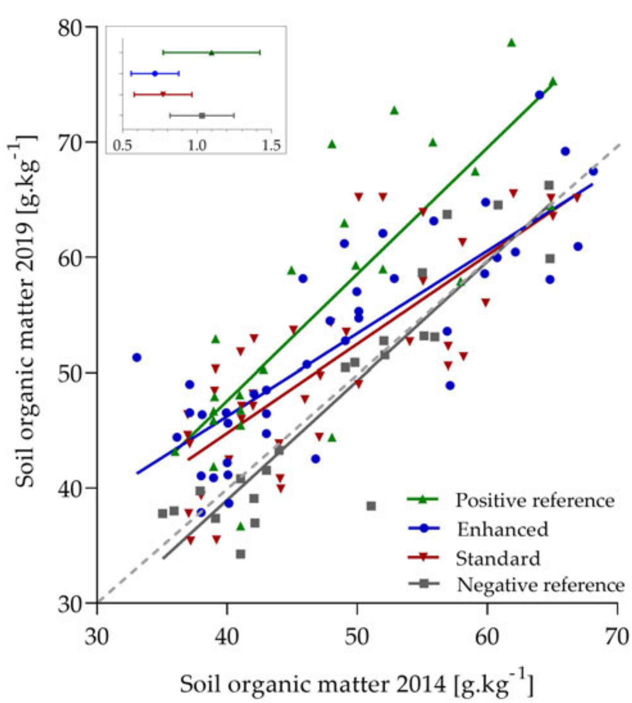

Figure 3. Labile carbon at 0–100 mm depth, plot of predicted means and 95% confidence intervals by treatment mg kg^{-1} (also see Supplementary Table S4).

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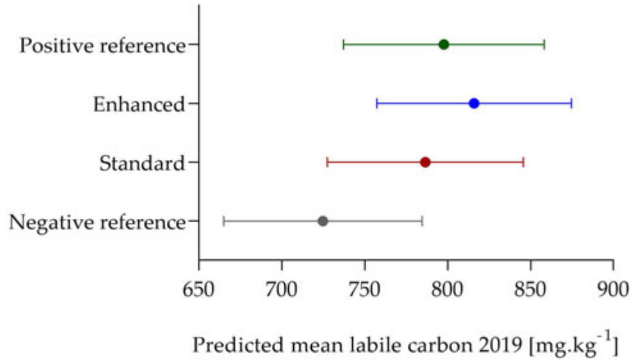

Figure 4. Scatterplot of SOM 2014 against SOM 2019 at 0–100 mm soil depth with linear regression lines (main figure). Experimental treatments refer to positive reference (green squares and line), enhanced (blue triangles and line), standard (gold circles and line), and negative reference (gray diamonds and line). Insert shows the slope of linear regression for each treatment, bars represent 95% confidence intervals, dashed line is 1:1.

irrespective of the initial level of SOM. The enhanced and standard treatments added SOM at a progressively diminishing rate. The difference between the treatments was significant (P = 0.032). The regression lines in these two treatments cross the one-to-one line at approximately 63 g kg^{-1} SOM, indicating a possible SOM plateau under current management practice. The maximum SOM content under the positive reference treatment appears beyond the observed range of the experiment.

Effects of soil depth

Bulk density varied between the experimental treatments across the three depths measured (0–100 mm depth: $P = 0.024$; 100–300 mm depth: $P = 0.016$; 300–500 mm depth: $P = 0.006$). The soil had lower bulk density in the positive reference at 300–500 mm depths than under any other treatments (Fig. 5 and Supplementary Table S7). The effect of the negative reference on bulk density did not vary with depth. The enhanced and standard treatments gave greater bulk densities at 100–300 mm compared to 0–100 mm depth. Water infiltration rates were not different between treatments ($P = 0.24$, see Supplementary information).

Discussion

The diverse ley cropping system in this study, whether shredded crop residues were retained or not, resulted in important increases in SOM. The amount of organic matter in the top 100 mm of soil increased by 1.59% in the enhanced treatment, 1.21% in the standard treatment, and 3.14% in the positive reference per annum over the 5-year study period. At the 100–300 mm depth, SOM did not change in the enhanced and standard treatments but increased by 1.57% in the positive reference. This easily surpasses the annual 0.4% COP21 global target of increasing existing SOC stock annually (Minasny et al., 2017). Interestingly, the negative reference showed no change in SOM despite virtually zero fresh carbon input. Clearly, introducing diverse leys into arable rotations could meaningfully contribute to climate change mitigation, as Paustian et al. (2016) suggested. Increased SOM accumulation due to ley development may improve soil structure and function, positively affecting ecosystem services such as drought resistance, flood prevention, and nutrient cycling as a result (Acton and Gregorich, 1995; Minasny et al., 2017; Paustian et al., 2016). Farmland biodiversity was shown to benefit from SOM increases due to impacts on above- and below-ground biota (Mader et al., 2002; Sylvain and Wall, 2011; Thiele-Bruhn et al., 2012).

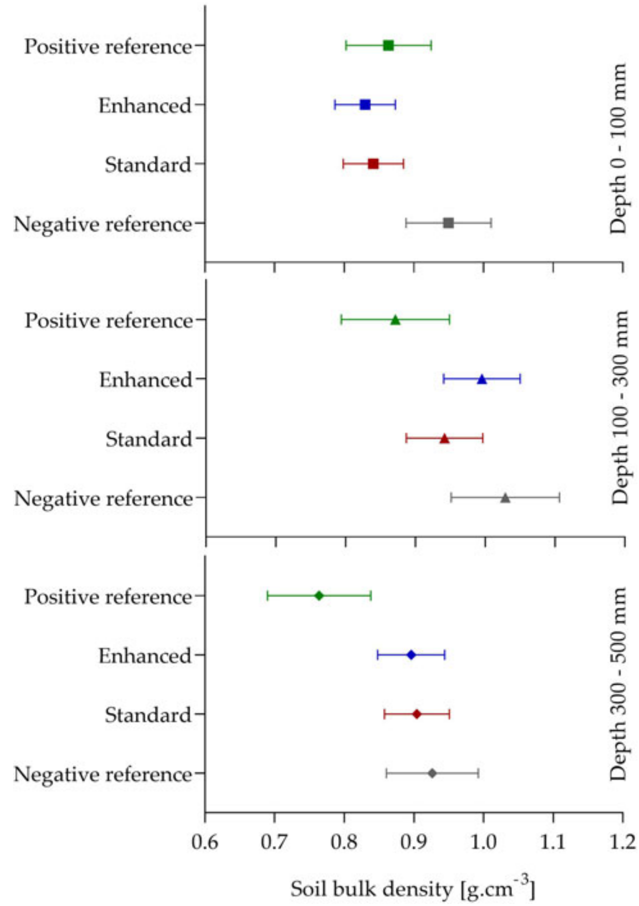

Figure 5. Soil bulk density in 2018, means by treatment at 0–100, 100–300, and 300–500 mm depths, bars represent 95% confidence intervals (also see Supplementary Table S6).

Lengthening the ley duration to 5 years increased carbon sequestration in SOM; there was a clear indication of greater carbon sequestration potential of this management option. Further, within the 5-year ley, we did not see upper limits established in the crop rotation treatments of this experiment; this treatment added 1.6 g kg^{-1} yr^{-1} SOM, irrespective of the initial level of SOM content. This differs from the enhanced and standard treatments, where the SOM increase was smaller in plots with higher initial SOM levels. The varying ability of arable soils to increase the absolute level demonstrated here has important consequences for soil carbon sequestration potentials (Amundson and Biardeau, 2018). Soil carbon concentration is a function of soil texture, climate, and management (Beare et al., 2014; Chung et al., 2010) and is driven by the soil microbial communities and enhanced by plant diversity (Lange et al., 2015), reaching a peak when the system is in equilibrium. Two long-term experiments in the UK in mixed farming systems attest to this. Firstly, a study at Woburn showed that a rotation of 2-year conventional arable with a grass/clover 3-year ley on sandy loam soil increased carbon by 0.28% (~4.83 g kg^{-1} SOM) after 33 years. Secondly, at Rothamsted, a 3-year arable with 3-year grass/clover ley on silty clay loam soil increased carbon by 0.23% (~3.97 g kg^{-1} SOM)

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over 36 years (Johnston, Poulton, and Coleman, 2009). These increases are smaller than those observed in our study, and the difference may be due to soil type, rotation diversity, use of tillage, or perhaps type of agriculture (conventional *vs* organic). In a US study converting row cropping to pasture with intensive grazing, Machmuller et al. (2015) observed a carbon sequestration curve reaching equilibrium after 6 years. Interestingly, our study shows that the carbon saturation point of agricultural soil can be increased using realistic changes to the cropping and land management systems.

More labile carbon was seen across all biomass addition treatments than in the negative reference. Increased labile carbon in the soil provides energy and nutrients that drive the physiology of soil microorganisms (Malik et al., 2018). These organisms then contribute to soil aggregation, stabilizing organic matter and improving soil function (Chantigny et al., 1997). Contrary to the work of Xu et al. (2011), there was no correlation between labile carbon content in 2019 and the rate of change in SOM in this experiment. In our case, this would suggest an alteration of the SOM transformation process (Liu et al., 2006), possibly due to crop residue quality or a shift in the composition of soil biota (Dignam et al., 2019). This study's diverse ley mixture of grasses, herbs, and legumes produced amounts of labile carbon similar to annual cereal crops. Several mechanisms may explain this, including an interaction between legumes and herbs driven by N availability (Carlsson and Huss-Danell, 2003), although we do not have data to explain this process fully.

Few changes in soil water infiltration or soil compaction were identified in this study. Bulk density in the enhanced and negative reference treatments worsened below tillage depth relative to the positive reference. However, we only measured bulk density on one occasion, making wider inference challenging. Organic matter content is associated with changes in soil physical attributes (Belmonte et al., 2018), but in our experiment, changes in SOM were not associated with a measurable change in bulk density. Water infiltration and its subsequent retention in the soil are important in buffering high rainfall events and mitigating drought and flood events, as soil compaction impacts water and air infiltration. The deterioration of these two soil properties in most arable systems typically hampers plant growth and soil organism activity, making tillage more difficult. Bhogal, Nicholson, and Chambers (2009) found that relatively large amounts of organic carbon inputs are required to change soil physical properties. However, we did not see any evidence of this process within the 5 years of the experiment, even in high biomass addition treatment. Longer-term soil improvements resulting from over 10 years of reduced tillage and the use of diverse leys with animal grazing at the site prior to the experiment may explain the lack of measurable effect (Reeder and Schuman, 2002).

We observed no decline in SOM in the negative reference treatment after 5 years of fallow treatment. The negative reference was routinely tilled to 75 mm for minimal plant growth. We expected the continued activity of heterotrophic organisms in the soil to slowly degrade existing SOM (Bellamy et al., 2005; Gougoulias, Clark, and Shaw, 2014), but we did not observe it. This illustrates the resilience of the soil system and the length of time needed to observe any changes in soil carbon content (Hendrix, Franzluebbers, and McCracken, 1998), particularly at sites such as ours where the lack of topographical gradient minimized erosion of bare soil (Montgomery, 2007).

Retaining crop residues in the enhanced treatment did not affect SOM or labile carbon relative to standard practice. Fertility-building diverse leys were integrated into all rotations observed in this experiment (except the negative reference). As the standard treatment did not retain any aboveground plant biomass, the root systems of the 2-year diverse ley are likely to have provided sufficient biomass input to result in no change in SOM and labile carbon compared to the enhanced treatment, which retained aboveground biomass. In a review of different cropping studies, root inputs were on average 8.1 times more effective at stabilizing SOM than the same mass of aboveground litter (Jackson et al., 2017). Our experiment implies that carbon sequestration begins with just 2 years of diverse ley pasture.

The diverse ley maintained throughout the experiment with no mechanical tillage (positive reference) was the only treatment that resulted in a significant change in SOM at the 100–300 mm depth. We saw a 3.0 g kg^{-1} SOM increase at this depth after 5 years and a reduction of bulk density at this depth. These effects may accrue from the bio-cultivation of soil, a combination of mechanisms driven by the interactions of diverse plant and soil biota communities (Mueller et al., 2013). The activity of roots at depth increases the movement of air, water, and biota through the soil and increases the aggregation of soil particles (Bardgett and van der Putten, 2014; Lavelle et al., 2006; Wagg et al., 2014). The diverse ley in the positive reference included several deep-rooting species, such as *Cichorium intybus*, *Onobrychis vicifolia*, and *Medicago sativa* (Wilkinson, 2020). In addition, the diversity of plant communities may be more important for deep rooting than the presence of plants with deep rooting traits (Mueller et al., 2013). The observed difference at 100–300 mm depth between the positive reference and the two biomass treatments suggests that the length of the ley phase (5 *vs* 2 years) appears to have more impact than returning crop residues to the soil (enhanced *vs* standard). Building up SOM, particularly at depth, may thus be more effectively achieved by growing diverse root communities rather than returning aboveground biomass to the soil.

Mixed ley farming systems can sequester amounts of carbon well beyond global targets. Our study shows that increased amounts of carbon can be sequestered by introducing leys into arable rotations and increasing the length of the ley phase. This strategy may have economic consequences for the farming system by reducing annual cropping and increasing animal utilization of the diverse ley. At a time when there is increased attention paid to animal production/husbandry as a driver of climate change, the use of diverse leys to support both ruminant and monogastric animal production (Fog, Ytting, and Lübeck, 2017; Santamaria-Fernandez et al., 2017) could make a significant contribution to off-setting their emissions (Dumont et al., 2020).

Conclusion

This experiment provides evidence supporting the carbon capture potential of diverse leys over a span of 5 years. However, a key finding suggests that the global impact of introducing diverse leys within a much shorter 2-year period could be equally significant. This intervention has the potential for widespread adoption in crop rotation systems as a means to mitigate climate change. Our results demonstrate that the accumulation of SOM in arable cropping systems is achievable, extending to depths of at least 100 mm, and at rates exceeding three times the COP21 global target of increasing soil carbon stocks by 0.4% annually.

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Data availability statement. The dataset used in this publication is available from the corresponding author upon request.

Author contributions. An early version of this article forms a chapter in a PhD thesis by R. G., submitted to the University of Reading. Conceptualization: R. G., H. E. J., and M. L.; methodology and data curation: all contributors; statistical analyses: R. G. and J. B.; writing and comments on original draft and writing—review and editing: R. G., J. B., and M. L.

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Code availability. Not applicable.

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