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To till or not to till in a temperate ecosystem? Implications for climate change mitigation

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Abstract

The management of agricultural soils affect the composition and scale of their greenhouse gas (GHG) emissions. There is conflicting evidence on the effect of zero-tillage on carbon storage and GHG emissions. Here we assess the effects of zero-tillage over a range of time frames (1–15 years) on carbon storage and GHG release and their controls in the UK Net global warming potential was 30% lower under zero-tillage systems, due to lower carbon dioxide fluxes, with the greatest impacts after longer periods of zero-tillage management. Simultaneously, in zero-tillage systems, soil carbon stocks and the proportion of sequestered recalcitrant carbon increased while the temperature sensitivity of soil respiration decreased with time, compared to conventionally soils. We conclude that zero-tillage could play a crucial role in both reducing GHG emissions and at the same time increase soil carbon sequestration, therefore contributing to mitigate against climate change. Our findings are particularly important in the context of designing new policies (for example the Environmental Land Management Schemes in the UK) that ensure the sustainability of agricultural production in a changing climate.

1. Introduction

Soils are a significant store of organic carbon (C), globally storing an estimated 1550 Gt C to a depth of 1 m [1]. Soils are also a substantial source of greenhouse gas (GHG) emissions, contributing one-fifth of global carbon dioxide (CO_2) emissions, one-third of methane (CH_4) emissions and two-thirds of nitrous oxide (N_2O) emissions [2]. Agricultural GHG emissions are complex and heterogeneous, but active management offers possibilities for climate change mitigation. Many of these mitigation opportunities use currently available technologies and can be implemented immediately [3]. Zero-tillage (where the seed is sown directly into undisturbed soil) is an increasingly popular strategy to minimise soil erosion, increase biological activity and promote greater soil aggregate stability [4, 5]. However, the extent to which zero-tillage reduces GHG emissions and increases soil carbon storage, compared to the more common agricultural practice of conventional tillage, is extensively debated in the literature and represents a crucial knowledge gap in the context of climate change mitigation [6].

Among the processes related with carbon release from soils, it is important to consider the possible function of many agricultural soils as carbon sinks [7]. Sequestered carbon transferred from the atmosphere to soil may be found in labile pools, with mean residence times in the order of months or years, or in recalcitrant pools with mean residence times of centuries [8]. It is also important to consider the 'protection' of sequestered carbon and not simply the 'stable' proportion of soil carbon [9]. Conventional agricultural practices accelerate the loss of soil organic matter by increasing the oxygen concentration in the soil profile, destroying soil aggregates, and exposing organic matter for mineralisation [10]. It has been proposed that zero-till systems could increase soil organic matter sequestration but the magnitude of such changes in carbon storage throughout the soil profile are uncertain. Previous studies have overestimated the benefits of zero-tillage by disregarding differences in the vertical distribution of soil organic matter [6, 11]. Zero-tillage can increase concentrations near the soil surface, but there is commonly a more uniform distribution of organic matter over a greater depth in conventionally tilled soils. The current Intergovernmental Panel on Climate Change (IPCC) method to quantify carbon sequestration in soil considers only the organic matter content at a fixed depth interval, so comparisons between management strategies that affect bulk density are biased because corresponding soil material is not compared [12]. The impact of conversion from conventional cultivation to zero-tillage on soil carbon stores must be assessed by comparison of equivalent soil masses (ESMs), rather than depth intervals, and should consider the persistence of additional carbon throughout the soil profile [6].

Soil CO_2 fluxes are the second-largest component of the carbon cycle and in order to mitigate climate change, reducing emissions from soil will be of critical importance [13]. Differences in CO_2 emissions between conventional and zero-tillage can result from both short- and long-term mechanisms in soil. Mangalassery *et al* showed 21% greater CO_2 emissions in response to conventional tillage compared to neighbouring zero-tilled soils, which was attributed to differences in the total soil porosity and pore size [14]. True climate change mitigation is only possible if the overall impact of zero-tillage adoption is to reduce the net global warming potential (GWP). This should be calculated by incorporating the three major biogenic GHGs; CO_2, CH_4 and N_2O [15]. For example, N_2O has a GWP 265–298 times that of CO_2 for a 100 year timescale [16]. It is important to consider the net GWP as changes in cultivation practices may increase fluxes of some GHGs and reduce those of others. The net effect is therefore a trade-off. Despite this, only a few studies evaluating the impact of tillage management have considered the combined effect of changes in fluxes of all three major GHGs [17–19].

Agricultural soils are vulnerable to climate change, which is predicted to result in a 0.7 °C–5.4 °C increase in temperature across the UK, by 2070 [20]. The temperature responses of GHG emissions from agricultural soils differ considerably among management practices, because of differences in lability of organic matter [21]. It is therefore critical that we quantify the potential feedbacks for climate warming from different agricultural managements. It is plausible that an increase in temperature further intensifies the climate burden of GHG from agriculture. It is also plausible that greater temperatures preferentially stimulate decomposition of more recalcitrant carbon as greater temperature sensitivity of organic matter decomposition is predicted for more recalcitrance compounds, as higher activation energies are needed for catabolism, in line with kinetic theory [22, 23]. However, in mineral soil protection, aggregates can reduce the vulnerability of organics to decomposition and temperature increases [24]. The temperature sensitivity of soil respiration is often expressed as the Q_{10} value, 'the increase of soil respiration by a 10 °C increase in temperature' [25]. This approach is implemented in several models, which influence policy and land managements, and usually employ a fixed value of 1.5 (e.g. CLM) or 2 (e.g. CASA and TEM), which is used for all soil managements [26, 27]. However, studies have demonstrated that the temperature sensitivity is variable, with Q_{10} values ranging from 1 to greater than 12 [28]. Zhou *et al* showed, on a global scale, that small inaccuracies with regard to Q_{10} may result in large errors in the estimation of carbon dynamics [29] and the need to understand the responses of soil respiration becomes critically important. Since both storage and emission capacities may be large, precise quantifications are needed to obtain reliable global budgets necessary for land-use managements, global change and for climate research.

This study addresses how the adoption of zero-tillage in temperate climates could be expected to affect climate change through changes in fluxes of the principle GHGs, and through carbon sequestration. To achieve this, the study addresses five specific hypotheses linked to how conversion from conventional to zero-tillage and temperature changes alter soil carbon lability and CO_2, CH_4 and N_2O fluxes whilst demonstrating the soil emission-related processes and the factors that influence them.

The first hypothesis (1) 'zero-tillage will increase carbon stocks measured on an equivalent mass basis' is based on the notion that long-term zero-tillage alters the functional groups of carbon through a modification of the soil pore architecture resulting in physical and chemical protection [30, 31]. Because substrate lability is often a predictor of GHG emissions in agricultural soils [32], we hypothesis that (2) 'there would be a reduction in GHG emissions compared to conventionally tilled soils, through changes of the soil porous architecture, protecting organic material from decomposition'. In line with kinetic theory [22, 23] we also hypothesise that (3) 'the impact of conversion on carbon persistence in soil is exacerbated by higher temperatures, with the largest differences between temperatures in conventionally tilled soils' due a lower persistence of organic carbon under conventional tillage. This study entails measurements from soils at 80 sites where paired samples could be collected from close-neighbouring sites under zero and conventional tillage. Zero-tillage had been implemented for different time periods (1–15 years) and since changes to soil structure in response to zero-tillage occur slowly, we hypothesised (4) 'that such effects on GHG fluxes and carbon storage from zero-tillage are enhanced over time'. Lastly, due to the large regional area included within this study, we hypothesised (5) 'that the observed effects would vary at regional scale due to variation of soil properties'.

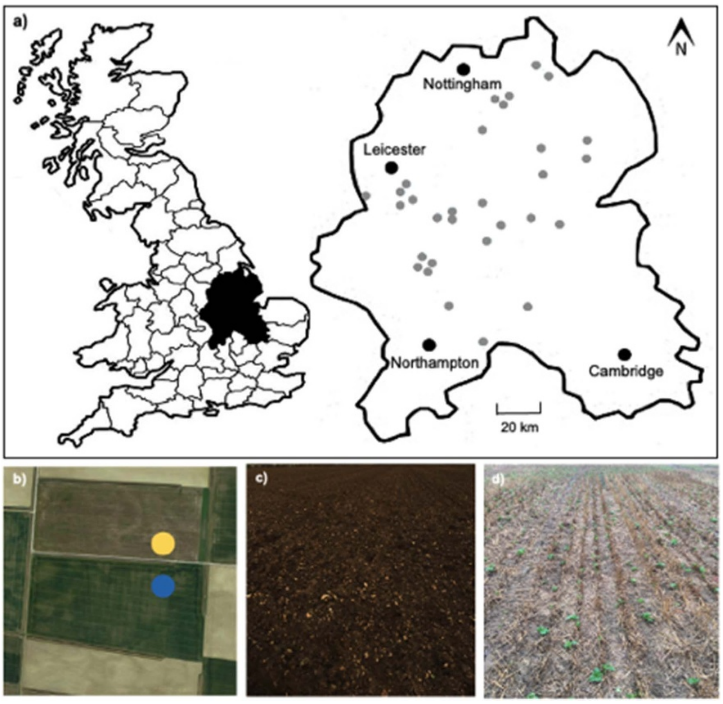

Figure 1. (a) The location of the 31 sampled farms (grey circles), where a maximum of three pairs of zero and conventionally tilled fields were taken from each farm until a selection of 80 pairs were collected. Adapted with permission from pixabay.com. An example (b) of a pair in Lincolnshire where the soil samples were not taken more than 10 m apart, the conventionally tilled field in shown in yellow (c) and the corresponding zero-tilled field shown in blue (d).

2. Methods

2.1. Site selection and sample collection

This study was conducted across the East Midlands of England in the UK covering an area of 6504 km^2 (figure 1 and supplementary table 2 (available online at stacks.iop.org/ERL/16/054022/mmedia)). Sites, 160 in total, were located in 80 pairs of commercially managed fields, each pair comprising one conventionally tilled field and one zero-tilled field. The fields in each pair were adjacent to each other and selected so that the sample sites were no further than 10 m apart. This was to reduce climatic and especially soil variability within pairs. Farmers were recruited to the study if they practiced zero tillage in a field with a close-neighbouring field under conventional cultivation. For this reason, samples were not selected independently and at random according to a probability sampling design. All zero-tilled soils had been managed this way for between 1 and 15 years, whereas the conventionally tilled soils were subjected to annual mechanical turnover to a depth of at least 20 cm. All sample collection was undertaken between November and December 2015, approximately 1–2 months after sowing cereals. The sampling and measurements carried out in this study represent a single point in time during the growing season and thus may not be representative for the whole growing season. However, this time of year, was pre-selected due to early and slow root growth in cold temperatures, ensuring changes to soil structure were minimised and access to the soil surface (without an established crop) could be readily achieved.

Soil sampling was undertaken approximately 4 m from the field boundary and not on the headland or on tractor wheeling's. Intact soil cores (5 cm diameter and 30 cm depth) were collected using a manual core sampler that used transparent sample liner tubes (Van Walt Ltd, Haslemere, UK) for x-ray computed tomography and GHG emission analysis. Additional intact soil cores (6 cm diameter and 15 cm depth) were also collected in a PVC cylinder for saturated hydraulic conductivity measurements. Samples of the surface soil were collected using a stainless-steel cylinder (7 cm diameter and 4 cm height) for the measurement of bulk density. A cone penetrometer (Rimik CP40) was used to measure the soil penetration resistance encountered at various depths, to a maximum of 60 cm, for accurate readings, the penetrometer was inserted into the ground at a steady state speed (c. 30 mm s^{-1}). To measure soil shear strength in the field, a Pilcon 120 kPa hand vane was used on the upper 50 mm of soil. To determine depth profiles in soil carbon, microbial biomass carbon (MBC) and nitrogen (MBN), soil water content and determination of organic matter functional chemistry soil samples were taken to a depth of 50 cm, in 10 cm increments, using a Dutch auger. All samples were kept at 4 °C prior to analysis.

2.2. Laboratory analysis

2.2.1. Soil physical properties

Soil was oven-dried at 105 °C and weighed to determine dry bulk density and gravimetric water content. Particle size analysis was performed using the hydrometer method [33] and textural classification made according to the Soil Survey of England and Wales classification [34]. Saturated hydraulic conductivity was determined using the standard constant head method [35]. Aggregate stability was estimated using a combination of methylated spirit and sieving through a cascading size of sieves, and expressed as the mean weight diameter [36].

2.2.2. X-ray computed tomography

Prior to the measurement of GHGs, 3D x-ray computed tomography (CT) was undertaken on all 160 intact soil cores in a Phoenix V|Tome|X m x-ray scanner 240 kV (GE Measurement & Control Solutions, Wunstrof, Germany) at the Hounsfield Facility at the University of Nottingham. This allowed visualisation and quantification of soil porous architecture. For a detailed description, see supplementary information 1.

2.2.3. Soil biochemical properties

Soil pH and MBC and MBN were determined for all surface samples (0–10 cm) and total soil carbon and nitrogen (N) was measured on the soil samples down to 50 cm at 10 cm intervals. Soil pH was estimated on a 1:5 soil–water mixture. MBC and MBN were determined using the chloroform fumigation method [37]. For this fumigated (for 24 h) and non-fumigated soils (10.0 $\pm$ 0.5 g fresh sample) were extracted with 0.5 M K_2SO_4 followed by analysis using a Shimadzu CN analyser (TOC-V CPH Shimadzu). The value of the coefficient (K_{EC}) to convert 'chloroform-labile' carbon to MBC of 0.45 was used [38] and for MBN (N_M) the value of K_{EN} was taken as 0.54 [39]. Total soil C and N was determined from 20 mg of oven dried, ball milled soil combusted using a total element analyser (Flash EA 1112, CE Instruments, Wigan, UK).

Five pairs of soils (0–50 cm in 10 cm increments) that had been under zero-till management for 1, 6 and 15 years were randomly chosen for determining organic matter functional chemistry. Fourier transform infrared (FTIR) absorption spectra were obtained with a Bruker Tensor 27 FTIR equipped with nitrogen purge gas generator and an mercury-cadmium-telluride detector. A total of 128 scans were performed on each oven dried, ball milled samples, and background spectra were run initially and after every eight samples. The spectral range spanned from 550 to 4000 cm^{-1} at a resolution of 1 cm^{-1}. All spectra were standardised, smoothed and baseline corrected (SpectraGryph v.1.2) before statistical analysis in order to allow direct comparison.

2.2.4. Potential greenhouse gas fluxes

Potential GHG fluxes were measured following incubation under a controlled environment. This approach was adopted to allow comparison between management by removing the effects of variable ambient environmental conditions on gas production *in-situ*. For a detailed description, see supplementary information 2.

2.2.5. Estimating carbon stocks

Soil carbon stocks were estimated by an ESM procedure to calculate carbon stocks in multiple soil layers (Mg C ha^{-1}) within a defined area using calculations from Wendt and Hauser [12]. This method quantifies and corrects for the fixed depth error associated with calculating carbon stocks as the product of soil bulk density, depth and concentration.

2.3. Statistical analysis

Model-based analyses were used, specifically a linear mixed model (LMM). For a more detailed description, see supplementary information 3.

3. Results and discussion

3.1. Response of soil carbon to long-term zero-tillage management

Our first hypothesis, 'zero-tillage would increase soil carbon on an equivalent soil basis' was rejected over all 80 pairs of zero and conventionally tilled soils (with mean stocks of 96 and 94 Mg ha^{-1}, respectively) (figure 2(a)). However, consistent with our fourth hypothesis, when time since adoption of zero-tillage was considered, significant effects on carbon stocks were found, with soils under zero-tillage storing 6 Mg C ha^{-1} more than conventionally tilled soils after 6–10 years, and 14 Mg C ha^{-1} more after 11–15 years, an annual increase of 0.6 and 0.9 Mg C ha^{-1}, respectively (figures 2(b)–(d)). The increase in carbon stock in long-term zero-tilled soils was attributed to the surface layers 0–10 and 10–20 cm, with no significant difference in carbon content between deeper layers (figures 2(b)–(d)). Simultaneously, conventionally tilled soils can lose total carbon, for example, over a 24 year period, conventionally tilled soils lost 8.2 Mg C ha, an average annual loss of 0.34 Mg C ha^{-1} [40]. This can include a substantial component from soil respiration, with tillage resulting in CO_2 emissions 13.8 times greater than paired zero-tilled soils [41]. It is important to note that rates of soil carbon sequestration reduce as the soil carbon stock approaches a new steady state (i.e. when soil carbon inputs approximate soil carbon outputs), and the soil carbon sink is saturated [42, 43]. The proposed time period necessary for soil organic carbon to attain a steady state varies between studies, ranging from 10 years to 100 years, depending on climate and soil type [44].

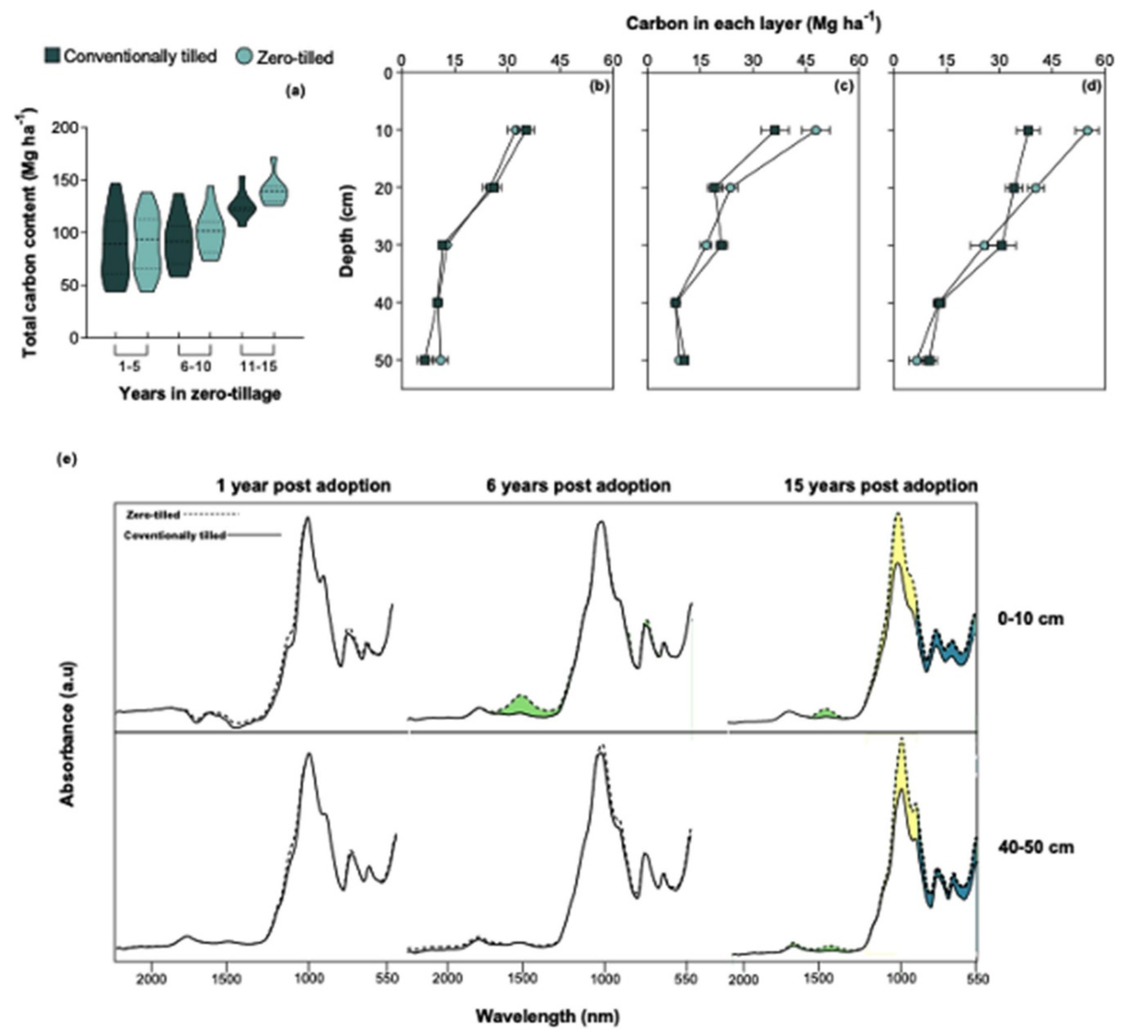

Figure 2. (a) Total carbon content under different managements, with first, median and third quartiles, and the shape showing distribution of individual data points. (b)–(d) Carbon in each soil layer from paired zero and conventionally tilled soils, shown on an equivalent soil mass basis. Soil depths, 0–10, 10–20, 20–30, 30–40 and 40–50 cm correspond to soil mass layers 0–1000, 1000–2000, 2000–3200, 3200–4500, 4500–6200 Mg ha^{-1}, respectively. Mean ± one standard error are shown and $n = 51$, 21 and 8 for soils under zero-till management for (b) 1–5, (c) 6–10 and (d) 11–15 years, respectively. (e) FTIR spectra to identify organic carbon composition at 0–10 and 40–50 cm for paired observations where soils had been under zero-till management for 1–5, 6–10 and 11–15 years. Green highlights differences in aliphatics, yellow in ethers and blue for aromatics. For the full FTIR spectra at the different depths, see supplementary figure 1.

We also found that soil functional organic chemistry, as inferred from FTIR data, was also influenced by duration of zero tillage; after 6–10 years aliphatic functional groups increased while after 11–15 years aromatic and ether groups increased, in soil taken from the 0–10 layer (figure 2(e) and supplementary table 3). At 40–50 cm, differences in organic carbon were observed in 15 years post conversion with an increase in ether and aromatic compounds (figure 2(e)).

Conversion to zero-tillage (>6 years) altered the distribution of carbon throughout the soil profile as inferred from comparison of paired soils under contrasting treatment. The largest increases in soil carbon occurred at the surface, with smaller increases occurring at depth until 30 cm where conventionally tilled soils had a larger carbon content. The additional soil carbon in the surface of zero-tilled soils mainly comprised material with aliphatic functional groups, which are associated with labile organic matter and are depleted following repeated tillage or soil disturbance [45]. In addition, a larger proportion of organic carbon of intermediate recalcitrance, (peak at 1004 nm, assigned to the ether functional group) was observed in long-term zero-tilled soils (>15 years). This organic carbon is less susceptible to oxidation on disturbance compared to labile carbon, and, in turn, increases the longevity of stored concentrations. The increase in recalcitrant aromatics in older zero-tilled soils suggests greater preservation of lignin during decomposition of crop residues and enhanced microbial stabilisation of organic materials, or both, contributing to further increased longevity of stored carbon. Although we demonstrate strong shifts in soil functional organic chemistry with conversion to zero-tillage, it is important to acknowledge that the

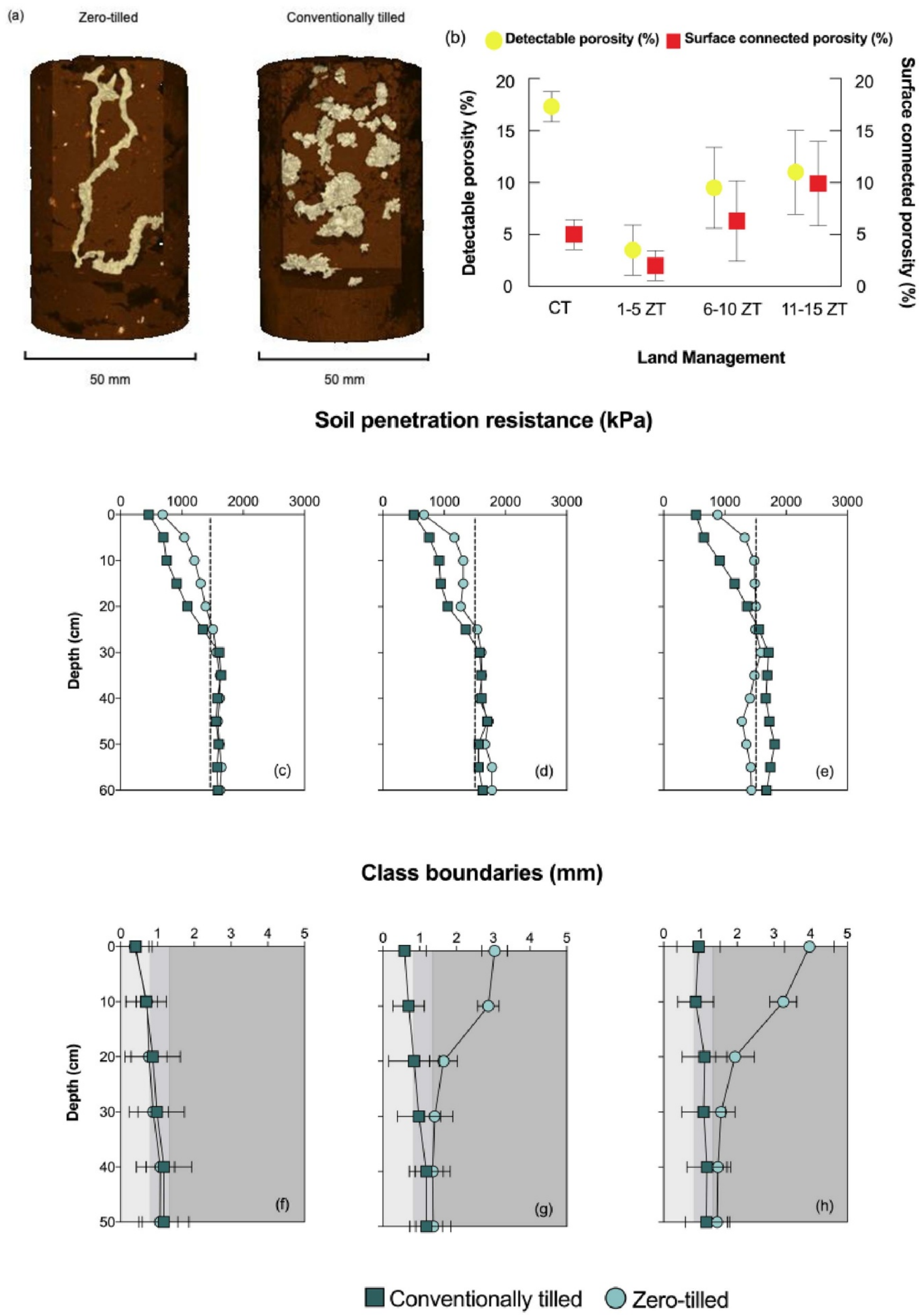

Figure 3. (a) Representative samples from zero and conventionally tilled intact soil cores using x-ray computed tomography. 3D images highlighting the surface connected porosity between the two treatments. (b) The detectable porosity (left y-axis) and surface connected porosity (right y-axis), as analysed using x-ray computed tomography at 50 μm. Soil cores had been in conventional tillage (CT), and between 1 and 5 (1–5 ZT), 6 and 10 (6–10 ZT) and 11–15 (11–15 ZT) years in zero-tillage (ZT). The soil penetration resistance (kPa) (c)–(e) and aggregate stability (f–h) in zero and conventionally tilled soils. The soils had been in zero-tillage for (c), (f) 1–5 years, (d), (g) 6–10 years, and (e), (h) 10–15 years. The dotted line (c)–(e) indicates 1500 kPa. Error bars are not shown as they are smaller than the symbols, see supplementary table 4 for means and standard errors of the means. The different shades of grey (f)–(h) indicate the degree of aggregate stability, with lighter shades showing unstable (<0.8 mm) aggregates, increasing to aggregates with medium stability (0.8–1.3 mm) and stable aggregates shaded in darker grey (>1.3 mm).

time for soil to reach a steady state for carbon storage will vary with climate, soil type and management practices [17].

3.2. Soil architectural changes gradually protects soil organic matter

Although total carbon did not differ across all zero and conventionally tilled pairs, we do demonstrate that 'long-term zero-tillage alters the functional groups of carbon through a modification of the soil architecture' (hypothesis 1) resulting in physical and chemical protection, and that these gains 'are enhanced over time as longer-term changes are brought about by the slow processes of soil development' (hypothesis 4) (figures 3(a)–(h)).

The dominant mechanisms by which organic carbon can be increased in soil are: (a) increased organic matter inputs, which is commonly associated with zero-tillage, (b) decreased rate of decomposition by biological or chemical means (figure 2) and (c) increased rate of stabilisation by physico-chemical protection within aggregates (figure 3). Increased stubble residue on the surface of zero-tilled soils provides organic matter for soil macrofauna, particularly for earthworms, which loosen the soil to greater depths by burrowing. Pelosi *et al* reported three to seven times more anecic and epigeic earthworms in zero-tilled systems than in cultivated soils [46]. The anecic species are highly sensitive to tillage operations due to their large size [47]. However, in zero-till systems, these species build permanent deep vertical tunnels through the soil profile (up to 2 m); increasing macroporosity, encouraging deeper rooting growth [48], transporting organic materials down, and, as shown in this study, increasing surface-connected porosity which is likely to assist infiltration and mitigate flooding (figures 3(a) and (b)).

A key concern regarding the adoption of zero-tillage is the increase in surface consolidation, which can result in farmers reverting back to conventional tillage typically after four-to-five years. Such reversion will result in the oxidation of recently stored soil organic matter and disruption of the complex network of biopores. Soils under zero-tillage for the greatest length of time (11–15 years, figures 3(c)–(e)), had a significantly reduced penetration resistance between depth intervals 35–60 cm compared to conventionally tilled soils, which may be attributed to the creation of an extensive biopore network. Allowing roots to penetrate deeper through the soil profile improves crops' access to water, and is a potential strategy to cope with the conditions expected from climate change (e.g. drought) [49]. Distinct differences in root distribution and total yield in compacted vs uncompacted layers have been previously shown [50]. Simultaneously, the increase in crop residue and bioturbation, coupled with a decrease in mechanical disturbance encourages the formation and increases the stability of soil aggregates in long term zero-tilled soils (figures 3(f)–(h)). These physical processes control the capacity of soil aggregates to resist exogenic action and to remain stable when exposed to changing environments.

3.3. Temperature sensitivity of conventional and zero-tilled soils

At 5 °C, there was no significant difference in CH_4 fluxes between tillage managements. However, in line with hypothesise 2, 'reduced GHG emissions under zero-tillage compared to conventionally tilled soils', the intact soil cores, when incubated at 10 °C and 15 °C, were a small source of CH_4 from conventionally tilled soils, whereas zero-tilled soils were a small sink (figure 4(a)). The duration since conversion to zero-tillage had no significant effect at any temperature. Conventional tillage can create inhospitable environments for methanotrophic organisms, destroying hotspots of methanotrophic activity and enhancing NH_4^+ production, therefore inhibiting CH_4 oxidation [51]. Conversely, the increased surface bulk density in zero-tilled soils can reduce CH_4 emissions by enhancing retention time and CH_4 oxidation [52]. The Q_{10} value, indicative of temperature sensitivity for soil respiration, for zero-tilled soils averaged at -1.88 ($\pm$0.4), compared to conventionally tilled soils which had a Q_{10} value of -0.05 ($\pm$0.3). Suggesting with an increase in 10 °C in temperature, zero-tilled soils will become a stronger sink of CH_4 fluxes compared to conventionally tilled soils. Previous studies have reported only gradual responses of CH_4 emissions to soil management, indicating that the recovery of methanotrophic activity in agricultural soil is slow [53]. Soils under zero-till soils might become a significant CH_4 sink only after several decades, suggesting this important ecosystem service is very vulnerable to tillage.

At 5 °C and 10 °C, there was no significant difference in N_2O fluxes between tillage systems. However, when incubated at 15 °C, zero-tilled soils produced significantly greater N_2O fluxes (0.118 mg N_2O m^{-2} h^{-1}) than paired conventionally tilled soils (0.085 mg N_2O m^{-2} h^{-1}). Greater N_2O fluxes from zero-tilled soils have previously been reported due to greater water and organic matter content [54]. As a result, there is greater microbial activity, consuming available O_2, creating anaerobic microsites and enhancing denitrification [55, 56]. In contrast, conventional tillage disrupts these microsites by increasing oxygenation of the soil [57], thereby reducing emissions. The duration of soils in zero-tillage had no significant effect at any temperature. There was no significant difference in Q_{10} values between the two managements, suggesting N_2O fluxes from both managements would have a similar response to an increase in temperature.

A 5 °C, there was no significant difference in CO_2 fluxes between tillage managements. However, when the soil cores were incubated at 10 °C,

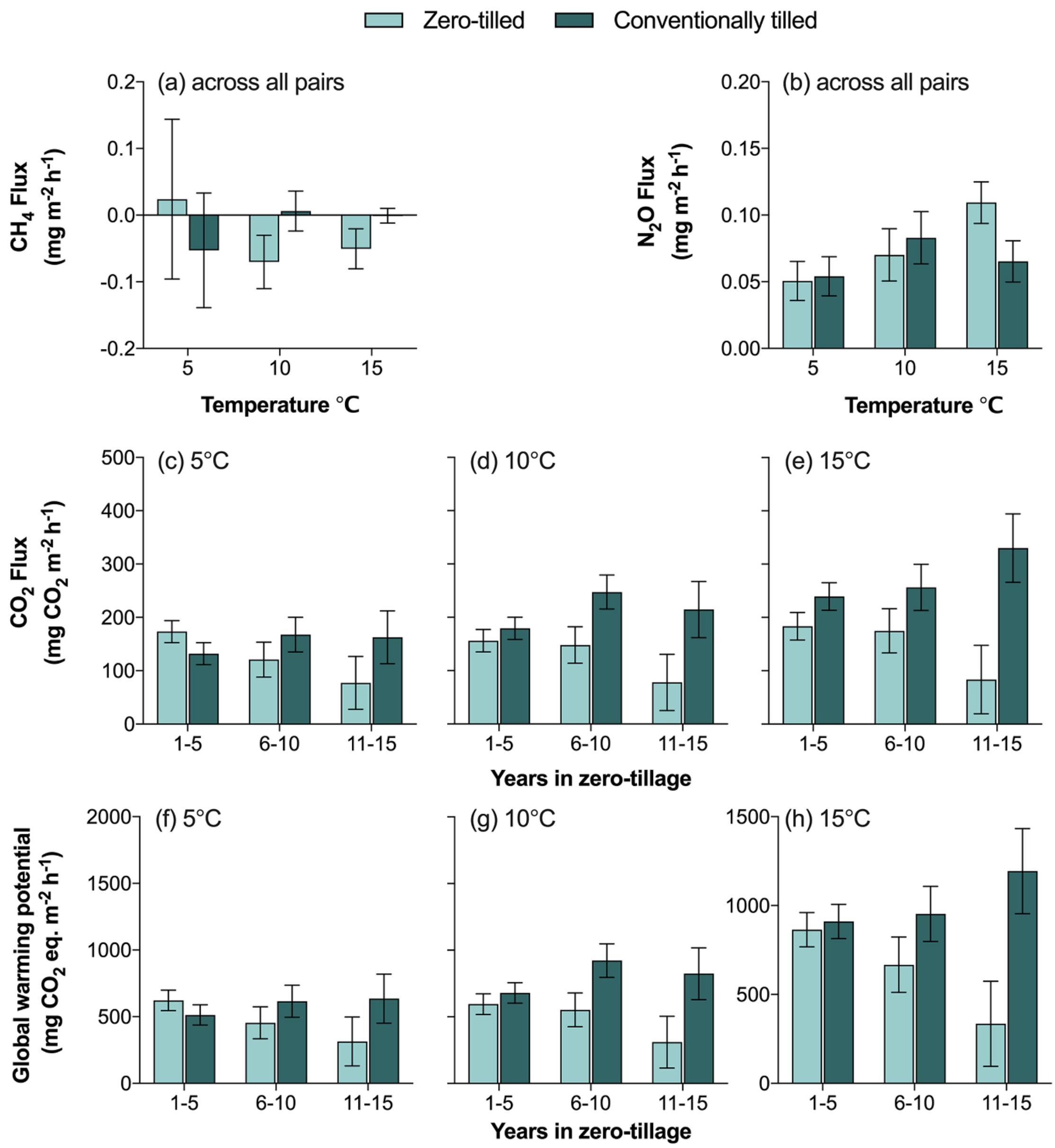

Figure 4. (a) Methane (CH_4) and (b) nitrous oxide (N_2O) fluxes from zero and conventionally tilled soils incubated at 5 °C, 10 °C and 15 °C. (c)–(e) Carbon dioxide (CO_2) fluxes grouped by length under zero-tillage with adjacent conventionally tilled pairs incubated at (c) 5 °C, (d) 10 °C and (e) 15 °C. (f)–(h) Global warming potential (GWP) grouped by length under zero-tillage with adjacent conventionally tilled pairs incubated at (f) 5 °C, (g) 10 °C and (h) 15 °C.

soil tillage significantly influenced CO_2 fluxes with greater fluxes from soils under conventional tillage (213 mg CO_2 m^{-2} h^{-1}) compared to zero-tillage (117 mg CO_2 m^{-2} h^{-1}) (figure 4(d)). When incubation occurred at 15 °C, similarly CO_2 fluxes were significantly greater from conventionally tilled soils (252 mg CO_2 m^{-2} h^{-1}) compared to zero-tilled soils (170 mg CO_2 m^{-2} h^{-1}), similar to Mangalassery *et al* [58]. Crucially, in line with hypothesis 3, when the soils under zero-tillage were grouped by time conversion, CO_2 fluxes were lowest for soils with the longest history of zero-tillage (figures 4(c)–(e)). Soil which had been in zero-tillage for the greatest length of time (figure 5(b)) were less susceptible to carbon oxidation at higher temperatures compared to the paired conventionally tilled soils. This has important implication for future climate models seeking to predict the effect of increasing temperature on soil carbon release from different agricultural managements. The smaller Q_{10} value reported for zero-tilled soils ($Q_{10} = 1.5 \pm 0.4$) suggests zero-tillage may mitigate the response of CO_2 emissions to increasing temperatures in conventionally tilled soils ($Q_{10} = 2.5 \pm 0.4$).

Critically, our study demonstrates when fluxes of all three GHG are considered, the potential GWP from zero-tilled soils, calculated as per the IPCC [59], was significantly smaller than at the paired conventionally tilled soils (figures 4(g) and (h)). The mean GWP of emissions from the zero-tilled soils was 33% and 36% smaller than that from the conventionally managed soils when incubated at

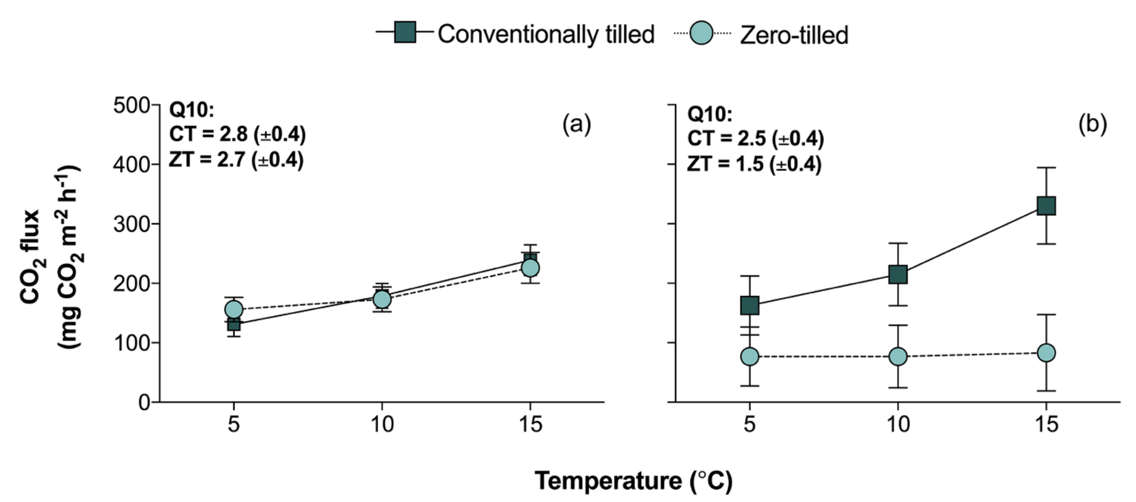

Figure 5. Q_{10} values estimated from soil incubations in (a) recently converted soils (1–5 years) and (b) soils which had been converted to zero-tillage for at least 11–15 years with adjacent conventionally tilled soils.

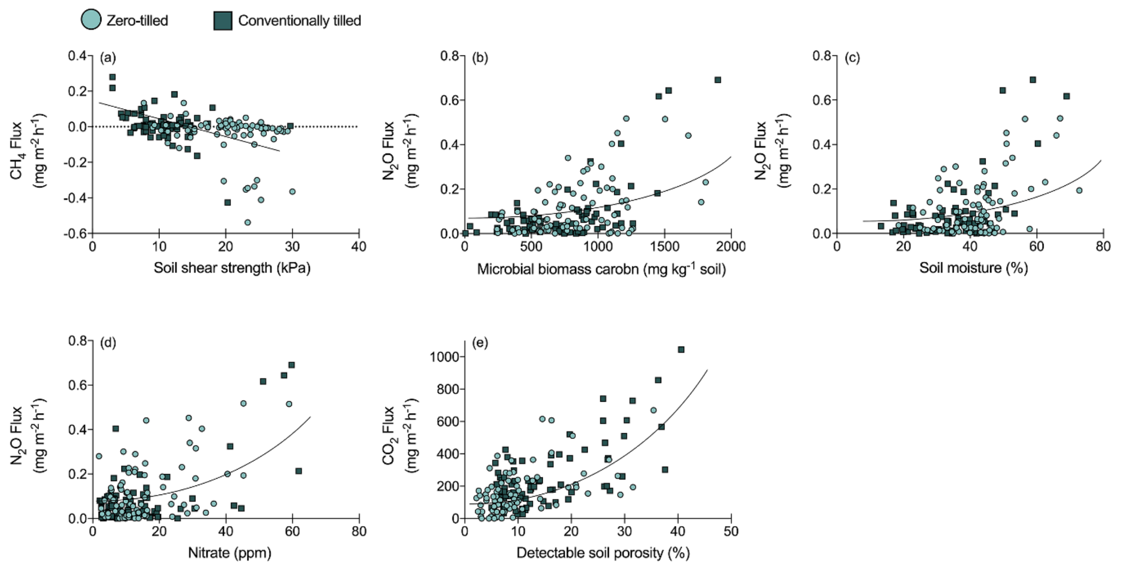

Figure 6. Relationships between soil biophysical properties and greenhouse gas release. (a) Surface soil shear strength and CH_4 flux from soil, (b) microbial biomass carbon (c) soil moisture and (d) nitrate concentrations and N_2O flux, and (e) detectable soil porosity, as measured by x-ray computed tomography, and CO_2 flux. Statistical analysis to accompany these figures are shown in table 1.

10 °C and 15 °C, respectively. The reduced GWP was driven by smaller CO_2 emissions and increased CH_4 oxidation rates. These findings are in line with a global meta-analysis which reported 66% smaller soil GWP *in-situ* from recently converted zero-tilled soils compared to conventional tillage [60]. We show that the reduction in potential GWP from zero-tilled soils increased substantially with time, with at least 75% lower emissions 11–15 years after conversion compared to paired conventionally tilled soils. It is plausible that some of the considerable variation in GHG reduction in the literature is linked to this temporal effect and suggests the full potential of zero-tillage climate mitigation potential might only be realised over time scales of >10 years [15, 61].

3.4. Drivers of GHG fluxes from different agricultural practices

Potential CH_4 fluxes were predicted by an LMM whereby soil shear strength accounted for 14% of the variation (figure 6(a)). The optimal model for the potential N_2O flux is shown in table 1. In this model, 35% of the N_2O flux could be explained by MBC, soil moisture and soil nitrate concentrations (figures 6(b)–(d)). Interestingly, yet not surprisingly, a large proportion of potential CO_2 flux (38%) could be accounted for by soil porosity alone, as measured by x-ray computed tomography (figure 6(e)).

We hypothesised that 'there would be a reduction in zero-tillage GHG fluxes compared to conventionally tilled soils, through changes of the soil porous architecture'. Our results suggest this is the

Table 1. Fitted linear mixed models for soil properties and greenhouse gas emissions from zero and conventionally tilled soils. Whereby κ is the value of the smoothness parameter, τ^2 is the uncorrelated or 'nugget' component, σ^2 is the spatially correlated random effects and ϕ is the value of the range parameter.

		Predictor and coefficient								
Predictand		β_0	β_1	β_2	β_3	R^2_{adj}	κ	τ^2	σ^2	ϕ
CH_4	Null model	—	—	—	—	—	—	0.0037	0.0012	71.2
			Shear strength							
		−0.122	−0.0042	—	—	0.14	2	0.0032	0.0010	108
N_2O	Null model	—	—	—	—	—	—	0.28	0.0056	337
			Microbial biomass carbon	Soil moisture	NO_3					
		−2.88	0.005	0.010	0.013	0.35	2	0.20	0.018	592
CO_2	Null model	—	—	—	—	—	—	85.8	6.96	3443
			Soil detectable porosity							
		12.9	0.7	—	—	0.38	2	55.5	2.44	2585

Table 2 Means, standard errors and statistical output from linear mixed modelling (management and duration i.e. time since conversion) for the physio-chemical characteristics of soils under zero (ZT) and conventional tillage (CT). Mean ± standard error of mean, $n = 80$, log likelihood ratio (L) shown for statistical output.

Variable		ZT	CT	Management	Duration	Management × duration
Moisture content (%)		41.8 ± 1.69	35.7 ± 1.67	32.6[a]	ns	ns
pH		7.14 ± 0.14	6.99 ± 0.14	ns	ns	ns
Microbial C (mg kg^{-1} soil)		497.6 ± 27.1	425.5 ± 27.1	6.1[a]	5.81[a]	14.0[b]
Microbial N (mg kg^{-1} soil)		46.7 ± 4.2	33.0 ± 4.2	15.4[b]	ns	ns
Bulk density (g cm^{-3})		1.33 ± 0.02	1.22 ± 0.02	15.7[b]	ns	ns
Porosity (%)		12.0 ± 1.4	16.4 ± 1.4	13.7[b]	20.1[b]	ns
Mean pore size 0–10 cm (mm^2)		0.49 ± 5.5	0.84 ± 5.5	24.6[b]	ns	ns
Mean pore size 10–20 cm (mm^2)		0.48 ± 8.1	0.76 ± 8.1	19.7[b]	ns	ns
Saturated hydraulic conductivity (cm s^{-1})		0.0056 ± 0.003	0.0124 ± 0.003	17.4[b]	3.3[a]	ns
CO_2 (mg m^{-2} h^{-1})	Incubated at 15 °C	169.8 ± 20.4	252.2 ± 20.4	9.6[a]	12.6[a]	7.7[a]
CH_4 (mg m^{-2} h^{-1})		−0.04 ± 0.021	0.007 ± 0.022	1.9[a]	ns	ns
N_2O (mg m^{-2} h^{-1})		0.118 ± 0.1	0.085 ± 0.1	4.8[a]	ns	ns
Global warming potential (mg CO_2 eq. m^{-2} h^{-1})		665.2 ± 76.3	950.8 ± 76.4	10.8[b]	10.4[a]	9.3[a]

ns: not significant.

[a] $p < 0.05$.

[b] $p < 0.01$.

case for soil CO_2 and CH_4 fluxes but that reduced porosity in zero-tilled soils is instrumental in reducing CO_2 fluxes, and thereby GWP. Crucially we also observed the subsequent and significant development of biopore channels by undisturbed biological activity in longer term zero-tilled soils which increased the surface-connected porosity (figure 3(b)). This, in turn, resulted in a significant increase by one order of magnitude in saturated hydraulic conductivity in zero-tilled soils over time from 0.003 to 0.01 cm s^{-1} for 1–5 and 11–15 years, respectively (table 2). Simultaneously, a greater saturated hydraulic conductivity in conventionally tilled soils can be attributed to a more porous soil architecture in the top 15 cm. This demonstrates that long term zero-tillage has the dual benefits of mitigating potential soil CO_2 fluxes, increasing CH_4 oxidation, and enhancing carbon storage through a reduction in soil porosity whilst reducing the risk of runoff during heavy rainfall through development of a highly effective, well-connected porosity.

In contrast, N_2O fluxes were governed more by substrate (nitrate and carbon) availability and soil moisture content rather than soil physical characteristics. This highlights the importance of regulating fertiliser input (e.g. using fertiliser at the correct time of year, using split applications and nitrification inhibitors) for controlling N_2O fluxes, and that changes in physical structure will have only indirect effects through changing soil moisture. We show zero-tillage can significantly reduce CO_2 fluxes, and increase CH_4 oxidation. Potentially through better management of residue inputs, N_2O fluxes could also be decreased, resulting in an even larger climate change mitigation potential of zero-tillage.

3.5. Regional variation in greenhouse gas and carbon storage

We assessed how these processes (GHG emissions and carbon sequestration) vary across a large region, hypothesizing that there would be substantial spatial variation (hypothesis 5). Across the East Midlands region, conventionally tilled soils had an average GWP of 950 mg CO_2 eq. m^{-2} h^{-1} ($\pm$76.4), compared to 665 mg CO_2 eq. m^{-2} h^{-1} ($\pm$76.3) from zero-tilled soils (when incubated at 15 °C). The variograms for GWP under zero and conventional tillage (supplementary figure 2) showed in both cases a substantial apparent intercept to the function showing short-range variation not resolved by sampling. For soils under zero-tillage, there was additional variation, spatially dependent up to about 10 km whereas this spatially correlated variation was very limited under conventional tillage. Consistent with this, the spatially interpolated potential GWP from conventionally tilled soils was uniform compared to zero-tilled soils. For conventionally tilled soils there was a GWP hotspot in the south-western part of the study area (850 mg CO_2 eq. m^{-2} h^{-1}), but over most of the study area the predicted GWP was in the range 650–700 mg CO_2 eq. m^{-2} h^{-1} (figure 7(a)). In contrast, predicted GWP from zero-tilled soils ranged from 200 to 800 mg CO_2 eq. m^{-2} h^{-1}, revealing considerable spatial heterogeneity (figure 7(b)). A similar pattern emerged from predicted C stocks, with uniform carbon stocks in conventionally tilled soils. In contrast, zero-tilled soils showed considerable variation in carbon stocks, ranging from 50 to 160 Mg ha^{-1} carbon across the area (figures 7(c) and (d)). The evidence we put forward from the East Midlands region in the UK demonstrates long-term zero-tillage can both substantially reduce potential GHG emissions whilst simultaneously increasing carbon stocks across a range of contrasting soil types.

Our findings contrast with those of Lugato *et al*, who suggest the mitigation potential of soil carbon management has been overestimated as a result of neglecting N_2O emissions in the long term [62]. However, Lugato *et al* used the LUCAS data set in which the soil was sampled to 20 cm depth only; such shallow sampling is unsuitable for addressing these questions as plant roots often extend much deeper [11]. In our study, which considers soil carbon stock changes to a depth of 50 cm, as well as the balance between the three major GHGs, zero-tilled soils sequestered more carbon compared to conventionally tilled soils when considering the temporal aspect, whilst the increased N_2O effluxes from zero-tilled soils were compensated for by reduced CO_2 and CH_4 fluxes.

The climate mitigation potential of zero-tillage also needs to be considered in the context of short- and long-term impacts on yield, as mitigation benefits at one site are of little value if reduced production is compensated for by cultivating more land. To date, the majority of studies report little or no difference in yield between the zero and conventional tillage managements [63–65]. This study was primarily based on incubations in the laboratory, whilst field measurements reflect field conditions more closely than measurements in the laboratory, they are also not without problems [66]. There is a delicate balance of advantages and disadvantages for both approaches, which were evaluated in light of the specific objectives of the study. GHG responses are variable over seasons, and this is true of most environmental properties, however the goal of our statistical approach was to look for evidence of an underlying signal (in this case, a difference between crop management methods) while dealing with the spatial variation as effectively as possible. We used a model-based approach in which the environmental variation which constitutes noise around our signal is modelled as a regionalised random variable. Our approach also allowed us, uniquely, to assess the precise geometrical composition of the pore space from the same sample in which the gas emissions were recorded which would not have been possible in the field.

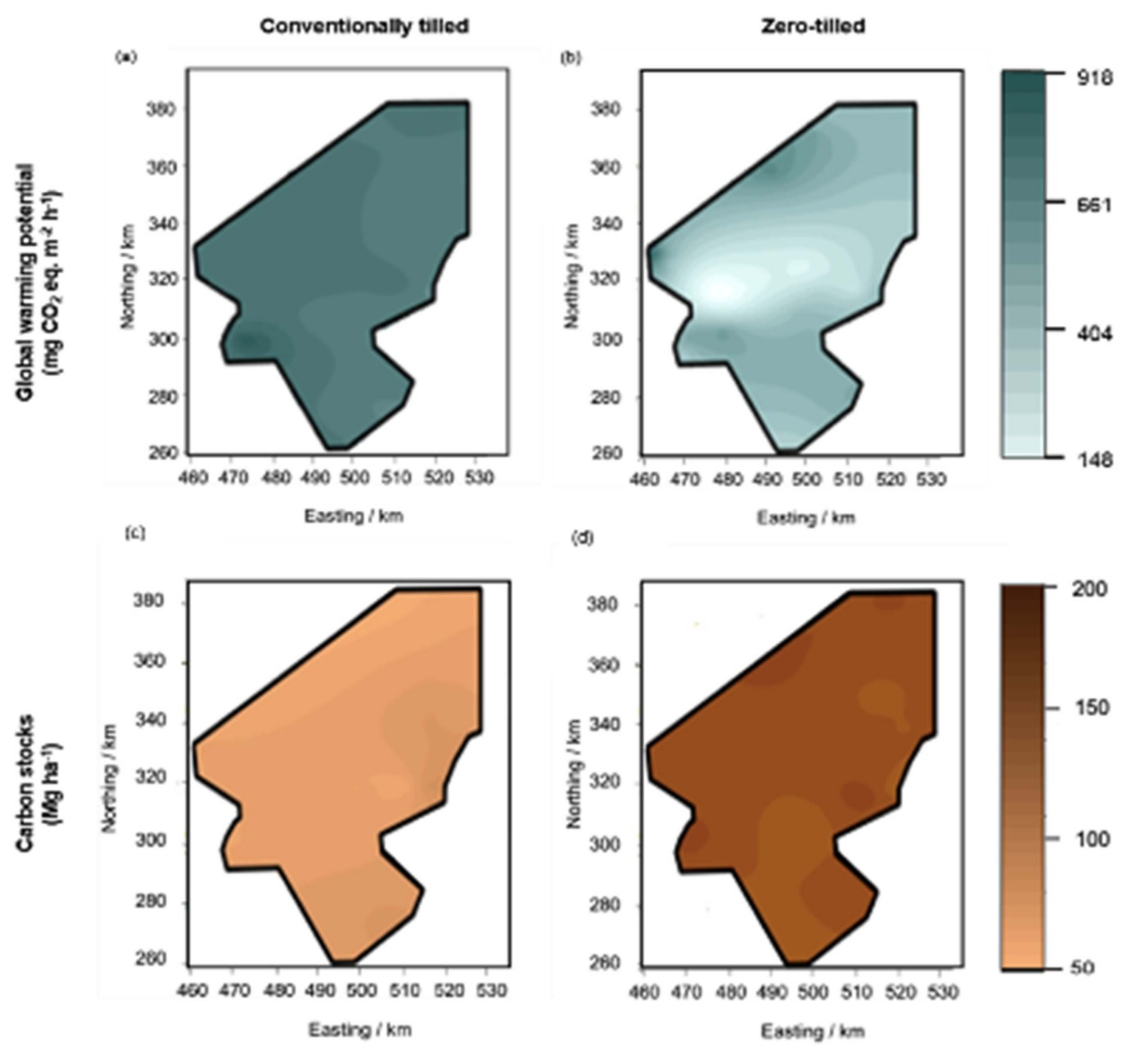

Figure 7. Predicted spatial co-variation of (a), (b) global warming potential in mg CO_2 eq. m^{-2} h^{-1} and (c), (d) total carbon stocks in Mg ha^{-1} in (a), (c) conventional and (b), (d) zero-tilled soils. See figure 1(a) in methods for geographical location. Note the scale bars are different within and between managements to illustrate the amplitude of differences. Co-ordinates are relative to the British National Grid-Ordnance Survey.

In conclusion, we demonstrate that zero-tillage can represent a 'win–win' situation, where in addition to CO_2 mitigation, other important benefits are achieved. Of particular significance to farmers is the role of long-term zero-tillage in improving soil quality through increased microbial biomass, the prevention of soil erosion and increased earthworm activity which thereby increases water infiltration. In addition to these benefits, zero-tillage reduces costs and labour requirements. For example, Smith *et al* suggested a 100% conversion to zero-tillage in Europe could mitigate all fossil fuel-carbon emissions from agriculture [67]. Our finding of at least 30% reduction in GWP after 10 years under zero-tillage highlights the viability of the practice as a key component for reducing cumulative emissions from UK agriculture. Given the urgent need for climate change mitigation to meet the 1.5 °C warming target [16] and to avoid the significant negative impacts of climate change on crop production, taken together, our results show that zero-tillage could be a key tool for reducing the carbon footprint of agriculture in temperate climates, including the UK.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

All authors contributed to the design of the study; H V C performed the soil and gas sampling and laboratory analysis; H V C and R M L analysed the data and H V C wrote the paper with contributions from S J M, R M L and S S.

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