

Article

Comparison of Compaction Alleviation Methods on Soil Health and Greenhouse Gas Emissions

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Abstract: Soil compaction can occur due to trafficking by heavy equipment and be exacerbated by unfavourable conditions such as wet weather. Compaction can restrict crop growth and increase waterlogging, which can increase the production of the greenhouse gas nitrous oxide. Cultivation can be used to alleviate compaction, but this can have negative impacts on earthworm abundance and increase the production of the greenhouse gas carbon dioxide. In this study, a field was purposefully compacted using trafficking, then in a replicated plot experiment, ploughing, low disturbance subsoiling and the application of a mycorrhizal inoculant were compared as methods of compaction alleviation, over two years of cropping. These methods were compared in terms of bulk density, penetration resistance, crop yield, greenhouse gas emissions and earthworm abundance. Ploughing alleviated topsoil compaction, as measured by bulk density and penetrometer resistance, and increased the crop biomass in one year of the study, although no yield differences were seen. Earthworm abundance was reduced in both years in the cultivated plots, and carbon dioxide flux increased significantly, although this was not significant in summer months. Outside of the summer months, nitrous oxide production increased in the non-cultivated treatments, which was attributed to increased denitrifying activity under compacted conditions.

Keywords: nitrous oxide; N₂O; carbon dioxide; CO₂; greenhouse gas; compaction; earthworms; direct drilling; bulk density



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1. Introduction

Soil compaction is a form of soil degradation, which is an issue worldwide, due to the detrimental effects it has on agricultural productivity, through reduced crop growth, increased soil erosion and nutrient depletion [1]. Within England and Wales, almost 4 million hectares of soil are at risk of compaction [2]. Compaction was identified by DEFRA as one of the three key threats to the agricultural and environmental productivity of soils [3] and one of the ten soil threats identified in Europe [4]. Although soil compaction is not a recent phenomenon, some modern farming techniques can exacerbate the risks, including increasing field size and weight of farm equipment [5,6]. In this study, we specifically looked at the impact of topsoil compaction exerted by trafficking, which can occur when soils are trafficked by heavy equipment, especially in wet conditions [7,8]. The susceptibility of soils to compaction depends on the interaction between soil physical properties and climate; often soils are workable when soil moisture is lower than field capacity, making the window of opportunity for poorly draining soils particularly narrow [5,9]. Heavy clay soils, such as those found at this experimental site, are therefore often prone to compaction when necessary field operations, such as harvest, coincide with wet weather. This may be exacerbated with the impact of climate change making weather patterns more extreme, with warmer wetter winters and increased occurrences of intense storms, potentially reducing machinery working days [10].

Compacted soils have less pore space, and increased bonding between particles, which leads to several problems. They will take more energy to cultivate, and aggregates will be harder to separate [11]. As pore spaces shrink, less space is available for water, and capillary attraction holding water within the soil increases, reducing water availability and plant uptake. Lower pore space and reduced infiltration also reduces soil aeration; this combined with restricted root growth impairs nutrient and water availability, reducing crop growth [9,12]. Compacted soils can also have detrimental effects on soil fauna, most notably, earthworms are often cited as being negatively affected by compaction, due to physical crushing and disruption of their burrow network [13]. Earthworms are also considered one of the key biological engineers needed to improve soil structure after compaction [14].

Due to the poor structure of compacted soils, they can become progressively poorer at absorbing rainfall, becoming more anaerobic over time without ameliorative action [14], which can affect microbial activity, subsequent nutrient cycling and greenhouse gas emissions. Carbon dioxide (CO₂) is produced through many microbial processes [15] and can spike immediately after ploughing due to the flush of CO₂ released from the mixing of the microbial community with decomposable substrates and aerated voids produced through tillage [16]. Pore space and pore connectivity allow for oxygen exchange within the soil, and when these are reduced, oxygen will deplete more rapidly leading to anoxic conditions [15] changing microbial activity. The microbial process of denitrification produces nitrous oxide (N₂O) and is greatest in wet conditions, so less plant available nitrogen can be found in the soil and more nitrogen is lost to the atmosphere as N₂ and N₂O [17]. As N₂O has a global warming potential 298 time higher than that of CO₂ [18], compaction has implications for global warming emissions as well as soil health and productivity.

The efficacy of three methods for mitigating compaction damage was compared with the direct drilled control to see, not only the impact of these methods on crop production, but also their impact on soil health and greenhouse gas emissions. Ploughing was used as the conventional cultivation method for alleviating topsoil compaction. As ploughing aerates the soil profile, it can accelerate the loss of soil organic carbon (SOC) to the atmosphere as CO₂, and destroy soil aggregates, exposing organic carbon for mineralization [19]. The physical process of running a plough through a soil can also have a detrimental effect on earthworm populations [13,20]. Both SOC and earthworm numbers have beneficial impacts on aggregate stability and soil structure [21], improving infiltration and resilience to future compaction. Low disturbance subsoiling (LDS) can be used as an alternative method of compaction alleviation, particularly in the subsoil layer, as the topsoil remains undisturbed. LDS theoretically has lower impact on CO₂ emissions due to the non-inversion nature of the cultivation, reducing the mixing and oxygenation of SOC, and potentially reducing damage to earthworms in the topsoil layers.

Due to poor root exploration in compacted soils and microbial processes occurring in waterlogged soils, there can be lower access to nutrients for plants [7,22]. Mycorrhizal association has been suggested to benefit plants in these conditions, as the excess hyphae network can scavenge nutrients from a larger volume of soil [23,24]. As a final compaction alleviation method, a mycorrhizal inoculant was introduced to help plants overcome the detrimental effects of compaction on nutrient acquisition. The overall aim of the study was to identify the detrimental impacts of topsoil compaction, and to compare methods of alleviating this compaction in terms of their impact on soil compaction, earthworm populations, plant productivity and greenhouse gas emissions.

2. Materials and Methods

The experimental area was set up in October 2017 at the Allerton Project—a 300 hectare mixed arable and livestock research, demonstration and education farm (Game & Wildlife Conservation Trust, Fordingbridge, Hampshire, UK), at Loddington, Leicestershire, UK (N 052°36'53" W 00°50'31"; 186 m a.s.l.). Soils are predominantly a heavy clay loam, UK soil series: Denchworth, texture 47% clay, 31% silt, and 22% sand, soil organic matter 4.2%. To create compaction in the field, a tractor (Massey Ferguson 7720, approximate weight

8 tonnes) was driven across part of the field (100 m × 50 m), so that every area of the plots had been passed over by a tractor wheel twice. The compaction was checked using a cone penetrometer (SC 900, Field Scout, Aurora, IL, USA), taking an average of 10 measurements per plot, and showing an average of 15% higher compaction measured across 45 cm depth, that peaked at an increase of 32% at 7.5 cm depth. Penetration resistance measurements were repeated 4 times across the year.

Plots were arranged across the compacted area in randomized blocks (with tramlines excluded from the experimental treatments), measuring 6 m wide and 40 m long, giving an area of 240 m². The effectiveness of cultivation at alleviating the compaction was tested using four treatments: plough, low disturbance subsoiler (LDS), mycorrhizal inoculant (AMF), and a no cultivation direct drilled control. Cultivations took place each year in autumn. Plough plots were ploughed to a depth of 25 cm, then disked to a depth of 10 cm (Väderstad carrier); LDS plots were subsoiled to a depth of 30 cm; AMF plots received a granular application of inoculant SR1:Cereals (Plantworks Ltd., Sittingbourne, UK) drilled with the crop at a rate of 10 kg/ha; while direct drill plots only received a straw rake before drilling. All crops were established using a direct drill (Eco M, Dale Drills, Market Rasen, UK) and standard farm practice was used for the application of manufactured fertiliser and plant protection products, which was consistent across all plots. Following cultivations in October 2017, *Hordeum vulgare* was planted across all plots and harvested in July 2018. The compaction and cultivation treatments were repeated in October 2018 keeping the same plot structure and *Vicia faba* was planted across all plots and harvested in September 2019.

Topsoil bulk density 0–10 cm was measured yearly in spring using a bulk density ring (10 cm depth, 5 cm diameter); three measurements were averaged per plot. Yield was taken from the combine as each plot was harvested. Plant biomass was also taken before combine harvest, by cutting three 0.25 m² quadrats per plot, and drying the biomass in an oven at 70 °C until a stable weight was achieved. Earthworm abundance was measured using three replicates of 20 × 20 × 25 cm soil blocks per plot that were removed by spade. Soil was sorted by hand and all worms were counted and weighed.

Greenhouse gas measurements were taken monthly across the two cropping seasons using an FT-IR gas analyser (DX4040, Gaset, Helsinki, Finland), set to measure CO₂ and N₂O simultaneously, with a 20 cm soil survey chamber attached (Li-cor). Plastic rings (20 cm diameter) were placed in the soil to a depth of 10 cm, allowing a 15 cm lip above the soil, at least 48 h before the first measurement. The chamber formed an airtight seal when placed on top of the rings. Gas flux was measured over 10 min, with the machine set to average measurements over 60 s. The initial 4 min were discarded to allow for gas equilibration in the system, and gas flux was calculated from the increase in gas concentration measured over the remaining 6 min. N₂O was multiplied by 298 to give an equivalent global warming potential to CO₂ to make comparisons between these two greenhouse gasses [18].

Statistical analysis used the Genstat software package [25]. A one-way ANOVA was used for all statistics, with the exception of the penetration resistance analysis. Where multiple measurements were taken, a repeated measures ANOVA was used. For penetration resistance, a principal component analysis (PCA) reduced the dimensionality of data, so comparisons between treatments at all depths could be made. PC1 (containing 75.53% of the overall variation) was used in a repeated measures ANOVA to test between treatments over the multiple measurement times.

3. Results

Penetration resistance showed significantly higher compaction in the uncultivated (AMF and control) plots ($p = 0.002$), which was mostly due to differences within the 7.5–25 cm depth range (Figure 1). There was also a significant impact of measurement time ($p = 0.008$) due to variation in soil condition over the year.

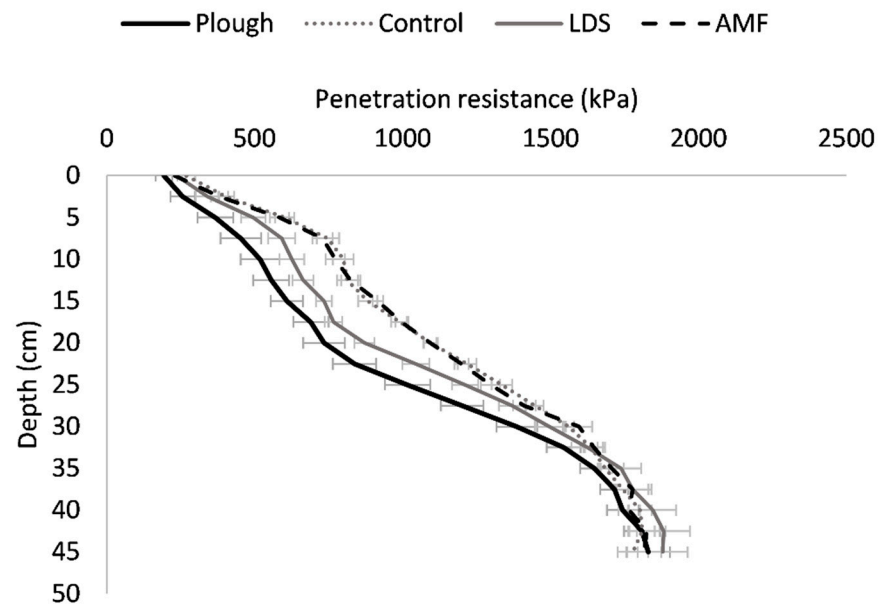


Figure 1. Penetration resistance (kPa) measured 0–45 cm depth through the soil profile. Graph shows average \pm SE of all readings taken across the two years of measurements.

Bulk density (0–10 cm) measurements only showed significant results in the first year. Bulk density was lower in the ploughed plots, but surprisingly, significantly higher in the LDS plots ($p < 0.001$) (Figure 2). Bulk density measurements taken in the second year followed the same trend, with plough the lowest and LDS treatment as the highest, but this was not significant.

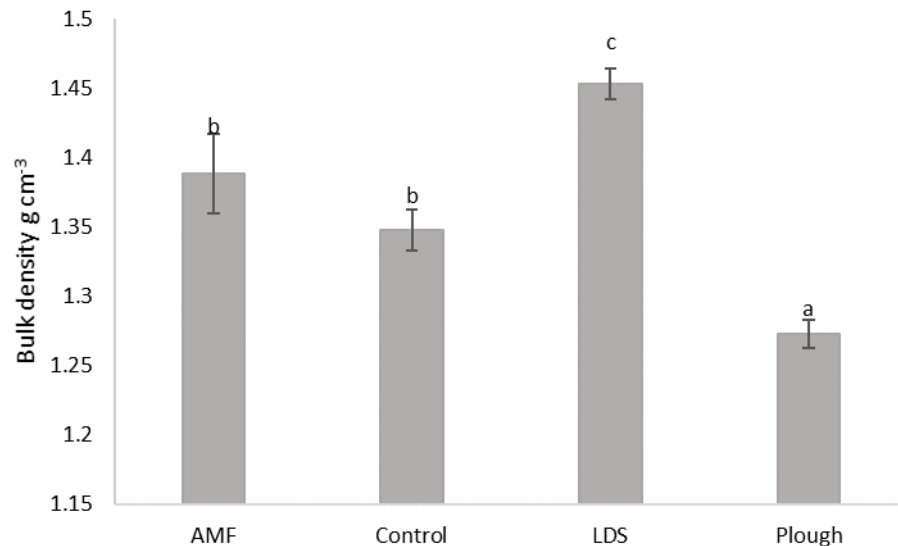


Figure 2. Soil bulk density (g cm^{-3}) measured in the topsoil 0–10 cm in 2018. Bars show mean \pm SE. Letters denote significant differences at $p < 0.05$.

Despite the measurable compaction, it was not strong enough to influence yield, with no difference seen in crop yield seen in the two years. For the 2018 barley (*Hordeum vulgare*) crop, overall plant biomass was significantly ($p < 0.001$) higher in the two cultivated plots (Figure 3), but no biomass differences were seen in the subsequent bean crop (*Vicia faba*).

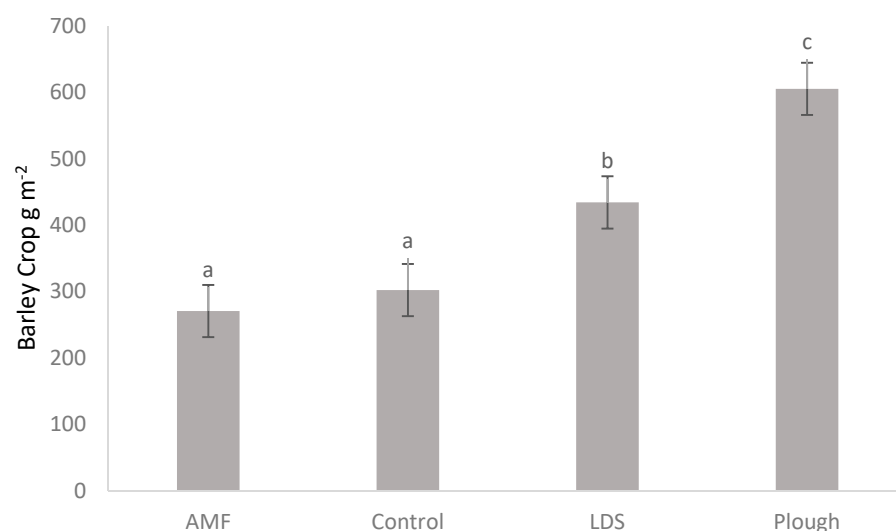


Figure 3. Barley crop (*Hordeum vulgare*) plant biomass measured in May 2018. Bars show mean \pm SE. Letters denote significant differences at $p < 0.05$.

Earthworm numbers were higher in the non-cultivated plots (AMF and control) in both years ($p = 0.046$) (Figure 4). There was a highly significant difference between years ($p > 0.001$), with 2019 having less than half the number of worms counted in 2018 (average 411 ± 65 in 2018, 172 ± 28 in 2019).

Earthworm abundance

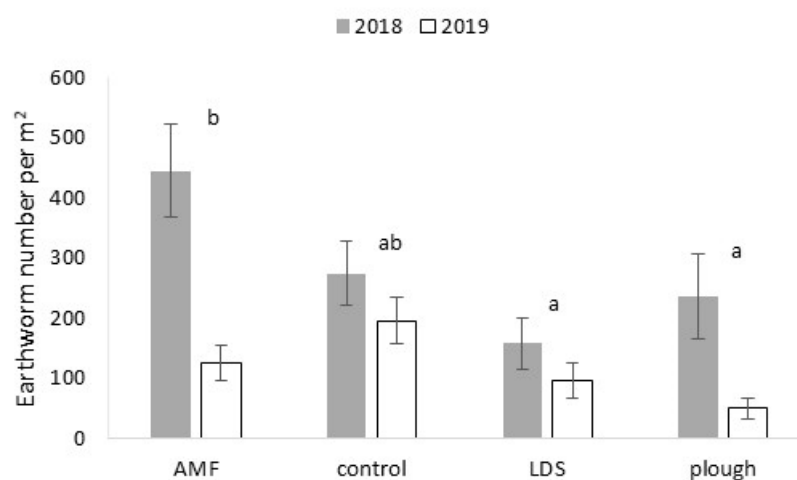


Figure 4. Average earthworm number (per m²) measured in 2018 and 2019, to a depth of 25 cm. Bars show mean \pm SE. Letters denote significant differences between cultivation treatments for both years at $p < 0.05$.

N₂O and CO₂ were measured monthly during cropping. Initially, repeated measures ANOVA showed no significant treatment effects for CO₂ ($p = 0.076$), however, splitting the results by season resulted in significant treatment effects for CO₂ flux in the winter months ($p = 0.034$), with ploughed plots having significantly higher CO₂ emissions (Figure 5). Initial N₂O emissions analysis showed significant treatment differences ($p = 0.046$), with significant differences between sampling times ($p < 0.001$) and a significant interaction between treatment and time ($p = 0.033$). Further investigation showed the interaction was due to much lower N₂O emissions during the warmer drier summer months. Breaking the analysis down into summer months (June, July and August) and all the other months (referred to as winter for simplicity), gave significant treatment effects for winter months ($p = 0.037$), with the AMF and the control plots showing much higher N₂O emissions

(Figure 6), but no significant effects were seen in summer months due to the overall lower emissions. The CO₂ and N₂O results were combined to give total green-house gas emissions for winter. The combined gasses showed no significant treatment differences in total gas fluxes recorded in winter ($p = 0.595$), although the composition of the gas fluxes changes between the plots.

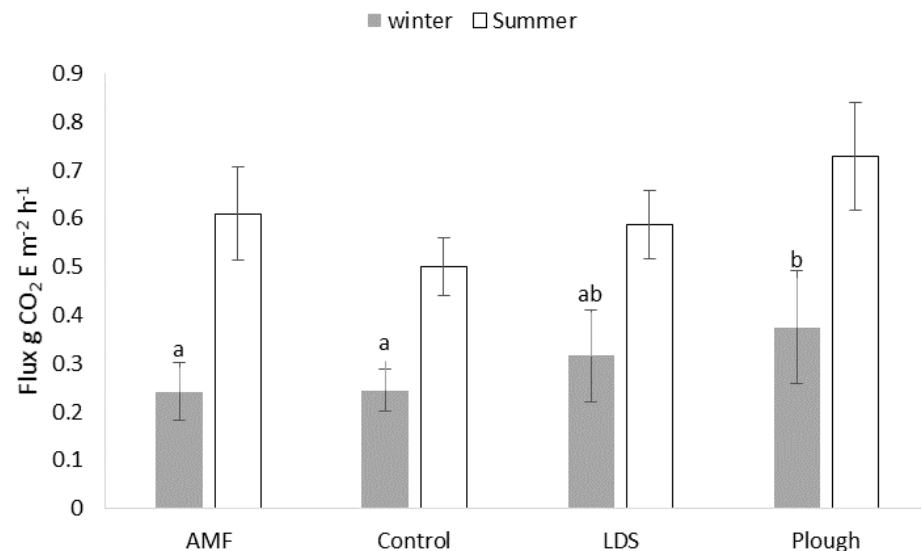


Figure 5. CO₂ flux measured monthly during 2018–2019 cropping and averaged over summer (June, July, August) and winter (all other months). Bars show mean ± SE. Letters denote significant differences between winter treatments at $p < 0.05$.

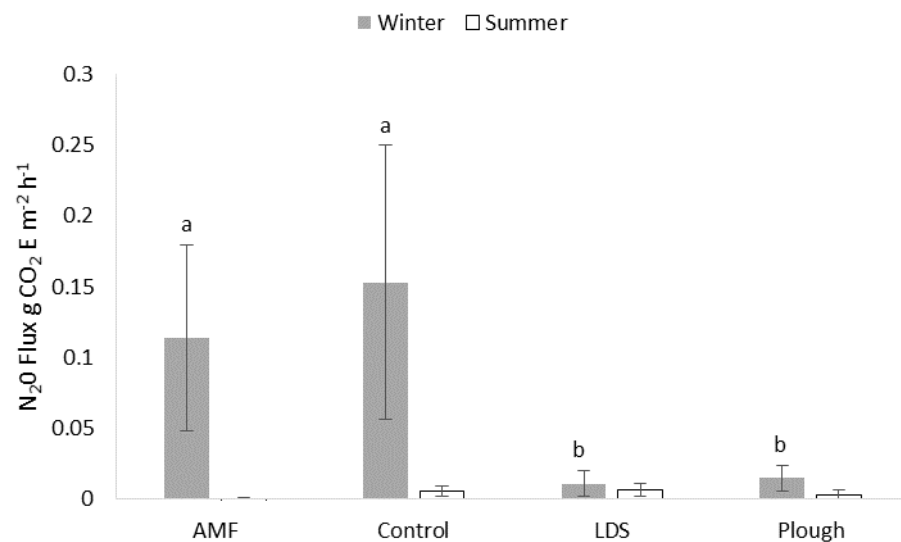


Figure 6. N₂O flux measured monthly during 2018–2019 cropping and averaged over summer (June, July, August) and winter (all other months). N₂O flux is displayed as CO₂ equivalent by 298. Bars show mean ± SE. Letters denote significant differences at $p < 0.05$.

4. Discussion

Direct drilling is established as a management practice that can improve aspects of soil health by leaving the soil undisturbed, which helps build soil organic matter and soil biology, such as earthworm populations. However, it does require soil to be in a fit state for conversion to direct drilling; compaction is a common problem across agricultural land, and can lead to issues including reduced root growth, reduced water and nutrient uptake and overall reduced productivity if not resolved with some form of compaction alleviation. This study compared the effectiveness of ploughing, low disturbance subsoiling

and mycorrhizal inoculation as compaction alleviation methods to direct drilling over a compacted area.

Uncultivated plots, AMF and the control plots had significantly higher compaction in the 7.5–20 cm range (Figure 1), when measured using a penetrometer. This is unsurprising, as this is the depth of soil that would have been influenced by the plough and the LDS cultivations. High penetration resistance scores of 1000–2000 kPa are linked with slower root elongation rates [26] and thicker roots, due to the increased pressure needed to penetrate the soil [27], which can be detrimental to plant growth as they require extra energy to explore the soil. A lower proliferation of roots can also result in reduced nutrient and water access for the crop. However, in this experiment compaction only reached above 1000 kPa at a depth of approximately 20 cm (Figure 1), suggesting that compaction in the topsoil where cultivation was used was not large enough to elicit a yield response. In 2018, a plant biomass response was seen in the barley crop, with smaller plants in the uncultivated plots (Figure 3). Previous studies have suggested that monocot crops are more capable of tolerating compaction than dicot crops [28], which could explain the difference between the response in the barley and the bean crop. Bulk density measurements taken in the top 10 cm of soil showed that ploughing resulted in the least densely packed topsoil, while LDS, surprisingly, resulted in the highest compacted topsoil (Figure 2). Subsoilers are designed to alleviate compaction at lower levels, leaving the topsoil relatively undisturbed. However, in some cases, subsoilers have been recorded to increase the compaction at the soil surface [29].

Earthworm numbers have been linked to improved infiltration [30], plant rooting depth [31], aggregate stability [21] and overall plant production [32], making them an excellent indicator of soil biological health [33]. Previous studies have suggested that earthworm populations diminish under cropping compared to pastureland, and under tillage compared to untilled cropped systems [34], which has been attributed to the mechanical damage and destruction of the earthworm habitat [20]. However, there is evidence that soil conditions such as high bulk density and low soil pore space caused by compaction can have adverse effects on earthworm populations, sometimes reducing numbers in uncultivated systems [35]. In the present study, earthworm numbers were significantly reduced under the cultivated treatments LDS and plough, across both years measured (Figure 4), suggesting mechanical damage had reduced the earthworm population, with potential detrimental effect on soil health and plant productivity in these plots. This highlights the trade-off between cultivation to alleviate the damaging effects of compaction, with the disturbance this causes on soil fauna needed for healthy soil processes. A long period of drought in 2018 is likely to have been a factor in the reduction in earthworm abundance between years. As the climate changes and the likelihood of prolonged droughts increases, these deleterious effects on earthworm populations will continue [36].

Direct drilling can reduce CO₂ emissions and lead to an overall accumulation of SOC, due to an increase in aggregate stability and a change in chemical composition of carbon to more recalcitrant forms [37]. N₂O is also a greenhouse gas emitted from soils, but with a far higher global warming potential than CO₂ [18]. The production of N₂O is primarily through denitrification, which increases when water-filled pore spaces within soils are around 65–75% [38]. As direct drilled soils generally have a greater bulk density, particularly if newly converted or previously compacted as in the present experiment, water-filled pore space is often higher favouring denitrification [39]. Bulk density measurements taken in this experiment were significantly lower in ploughed plots, suggesting that water-filled pore spaces would be similarly lower under the ploughed treatment (Figure 3). Higher bulk density was seen in the LDS plots, but this was only measured in the top 10 cm, as the LDS is designed not to disturb the topsoil, but to alleviate compaction at lower depths; there may still have been higher pore space lower down in the soil profile, which the penetration resistance measurement confirms (Figure 1).

Greenhouse gas flux measurements showed overall higher CO₂ emissions in the summer months (June, July and August), when soil activity is at its highest due to warmer

temperatures. No significant treatment differences were seen in CO₂ emissions between treatments in these warmer months, but when all other months were analysed together, significantly higher CO₂ emissions were seen from the two cultivated treatments, LDS and plough (Figure 5), due to the mechanical stimulation of organic matter breakdown in the soil [16]. In contrast, N₂O was produced at a much higher rate during the winter months than the summer months. During the winter months, there was significantly higher production of N₂O under the two non-cultivated treatments, AMF and control (Figure 6). These results are similar to those seen by Gregorich et al. [40], who found an increase in N₂O production in compacted soils, which corresponded to precipitation and high soil water content and was not seen in uncompacted treatments under the same conditions. Similarly, additional experiments at the site of our experiment, which used direct drill treatments without prior compaction have not shown this increase in N₂O flux (data not shown). Therefore, the increase in N₂O flux seen within this experiment was attributed to the reduced pore space, and subsequent increased water-filled pores in the compacted soil during the wetter winter months, causing an increase in denitrification activity and N₂O emissions. This has implications for compacted soils exacerbating N₂O emissions under future climate predictions of warmer wetter winters [10].

5. Conclusions

Overall, the efficacy of three methods of mitigating compaction damage to soil health and greenhouse gas emissions were compared with a direct drilled control. Two methods tried to improve soil structure and reduce compaction mechanically in situ, whilst the third, a biological method, attempted to reduce the impact of compaction on plant growth and nutrient acquisition. This study highlighted that compaction alleviation techniques differ in their efficacy as well as differing in their impact on soil health and greenhouse gas emissions. Earthworm abundance, a key indicator of soil health, was significantly reduced in the mechanical alleviation treatments, whilst emissions of CO₂ also increased. However, the link between compaction and increased N₂O emissions during wetter months is concerning, as seen in the AMF treatment and the direct drill control. Considering around 30% of soils in Europe are at risk (or susceptible) to compaction [4] and that winter rainfall is expected to increase due to climate change [18], greenhouse gas emissions may increase, dependent on agricultural (mis)management. This study highlights the importance of understanding how to alleviate compaction if we want to reach our climate emission goals and become net-zero within agriculture by 2040.

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