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RESEARCH ARTICLE

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Working with UK farmers to investigate anecic earthworm middens and soil biophysical properties

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Abstract

The conversion from conventional tillage to no-tillage soil management practices is generally associated with an improvement in aggregate stability and anecic earthworm populations. We worked with UK farmers who measured *Lumbricus terrestris* midden area (%) and earthworm numbers associated with middens compared to the general soil. They found that middens covered up to 42% of the soil surface. Middened soil (i.e., soil underlying the middens) was associated with significantly more earthworms than the general soil (i.e., non-middened soil) in agreement with research from scientific field trials. We compared the biophysical properties of middened soil to general soil across an experimental field trial recently converted to no-tillage soil management practices. We measured water-stable aggregation, soil porosity at scales relevant to water storage and gas diffusion and invertebrate feeding activity. Middened areas covered up to 13% of the field trial and were associated with significantly improved aggregate stability and porosity compared to the general soil. Our findings highlight the importance of considering middens when surveying soil quality and health in arable systems.

KEYWORDS
aggregate stability, agriculture, community science, earthworm, *Lumbricus terrestris*, midden, participation

1 | INTRODUCTION

Achieving sustainable soils by 2030 is a policy aspiration of the Department of Environment, Farming and Rural Affairs (DEFRA), for example, tackling the >2 million tonnes of topsoil eroded in England and Wales every year (Environment Agency, 2004). Changing from conventional tillage to no-tillage practices leads to a recovery in aggregate stability (Kibblewhite, Ritz, & Swift, 2008). Stable soil aggregates are principally built and regulated by soil biota (Six, Bossuyt, Degryze, & Denef, 2004). Mechanisms include: microbial exudates, hyphae enmeshment and roots binding soil aggregates and particles together (Tisdall & Oades, 1982).

The adoption of soil conservation practices tends to be governed by heuristics, with farmers adapting ideas from their trusted peer network (Coughenour, 2003) rather than working with scientists. This can be inefficient as a result of misunderstandings and maladaptations (Carmona et al., 2015; Findlater, Kandlikar, & Satterfield, 2019). However, farmer attitudes to soil degradation and soil health reveal a clear preference for farmer-to-farmer learning compared to policy mechanisms such as direct payments for soil management actions (Wheeler & Lobley, 2021). This indicates that community science could be important to sustainable soils. Citizens excel at measuring the visual properties and activities of earthworms, first recognised by Charles Darwin (Darwin, 1882). Earthworms have cultural significance in the United Kingdom, for example, we have found that farmers are willing to spend time measuring their populations and use this biological information to inform soil management actions (Stroud, 2019).

We hypothesised that there are hotspots of aggregate formation and stabilisation at the soil surface resulting from the above-ground actions of the native anecic earthworm *Lumbricus terrestris*. Middens are 5–15 cm diameter piles of plant debris that are gathered and maintained by *L. terrestris* earthworms that overlie their semi-permanent vertical burrow. Middens cover large areas of the soil surface in no-tillage arable fields (Subler & Kirsch, 1998) and are biological and chemical hotspots (Stroud, Irons, Carter, et al., 2016; Subler & Kirsch, 1998; Wilcox, Domínguez, Parmelee, & McCartney, 2002). These middened areas could help to explain the recovery in aggregate stability when soils management is changed from conventional tillage to no-tillage practices. However, *L. terrestris* is a tillage-sensitive earthworm (Briones & Schmidt, 2017), no-tillage is uncommon in the United Kingdom (Alskaf, Sparkes, Mooney, Sjögersten, & Wilson, 2019) and farmland earthworm surveys indicated that anecic earthworms (or their middens) are uncommon in approximately 20% fields in England (Stroud, 2019).

A group of farmers (BASE-UK) had requested information from the first author on 'scientific advances in earthworm science' and we used this opportunity to develop a community science activity. We had previously found higher earthworm populations associated with middened areas on our minimum tillage field trial (Stroud, Irons, Carter, et al., 2016) and we invited BASE-UK farmers to share their observations of middens (% surface area) and earthworm populations associated with middens vs general soil on their fields. The experimental field trial was recently converted to no-tillage at a site with a long history of conventional tillage and poor aggregate stability (Avery & Catt, 1995). We measured the area of soil covered by *L. terrestris* middens and compared with previous experimental applications of compost or farmyard manure (FYM) treatments to investigate residual effects. To test our null hypothesis that there was no significant difference between middened vs general soil patches, we performed biophysical assessments on sample pairs of middened and general soil. This included comparing in situ invertebrate feeding activity, and laboratory water-stable aggregation tests, porosity at scales important for water storage and gas diffusion in both clods and aggregates using X-ray CT scanning.

2 | MATERIALS AND METHODS

2.1 | Community science with farmers

BASE-UK is a farming organisation with members adopting three principles: minimum soil disturbance, residue cover on the surface and rotations. The first author was invited to present 'advances in earthworm science' at the BASE-UK annual general meeting that created an opportunity to coproduce information and present the results at the meeting. An email was circulated by the secretary with a simple method for use between October 21 and November 7 and a photo template for earthworm recording was provided:

1. Take a photo pointing down at the ground (midden area).
2. Dig up a midden (20 cm × 20 cm × 20 cm) and hand sort the soil for earthworms. Count and record.
3. Dig nearby (few metres) where there is no midden (general soil), 20 cm × 20 cm × 20 cm, hand sort the soil for earthworms. Count and record.
4. Upload your results.

Through uploading results, informed consent was provided, but no personal identifying information was requested or recorded (i.e., the survey was anonymous). The uploaded midden photographs were resized to 10 cm × 7.5 cm and overlaid with a grid (100 units) so that the area of the soil surface covered by middens could be calculated as a percentage (%). Photographs of the earthworms found were provided by some of the participants.

2.2 | Field trial

The NZ field trial was located at Rothamsted Research Farm (51.82 N and 0.37 W), Harpenden, UK which has a temperate climate in the South of England. The soil is characterised as a flinty silty clay loam of the Batcombe series, with total SOC 2.2% (LECO) and pH 6.9. The field had been in long-term (>100 years) conventional tillage (3-furrow plough to 23 cm) arable agriculture, with reduced tillage management started in 2012. In 2012, a 75-plot (8 m × 4 m plot size) randomised factorial block experiment was established and previous experimental details are reported elsewhere (Whitmore et al., 2017). There were no significant effects on soil biology or structure as a result of the annual applications of compost or FYM, but the trial is maintained in an arable rotation to assess the residual effects of these treatments (Whitmore et al., 2017). No experimental treatments were applied in the 2017–2018 arable rotation, but the trial was converted to zero tillage with crop establishment of winter beans using a very low soil disturbance Weaving GD Drill (Weaving Machinery). This crop failed and was sprayed off using a glyphosate-based herbicide in March. Spring beans (cv. Fuego) were drilled and taken to harvest instead. This crop received no fertilisers, but one 5 kg ha^{-1} application of a methaldehyde-based molluscicide and one 75 ml ha^{-1} application of a lambda-cyhalothrin based insecticide for crop protection against pests.

2.2.1 | Soil collection for laboratory analyses

A soil corer (75-mm diameter steel ring) was used to collect a soil sample to 50-mm depth from selected plots and placed into individual plastic boxes for transportation to the laboratory. For the 'middened' soil, the midden removed from the soil surface and the soil corer was used to collect the soil directly below the midden. For its

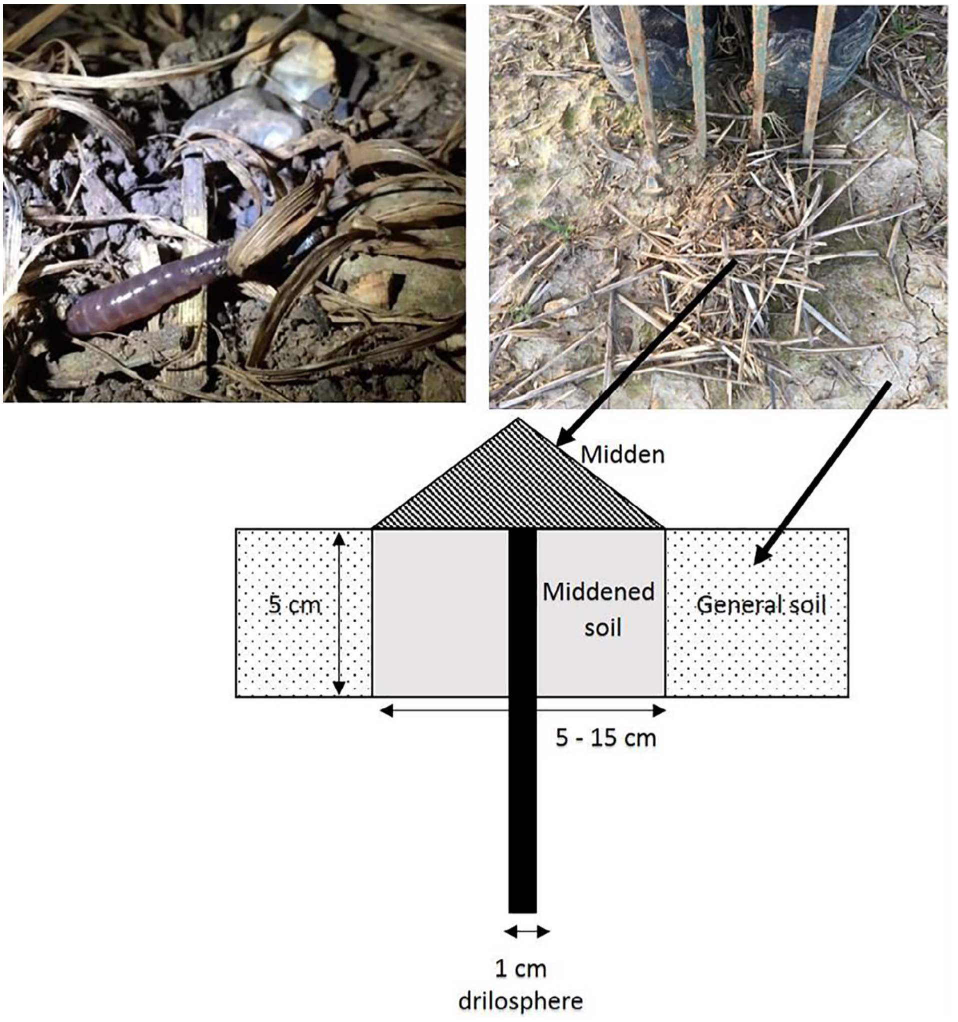

FIGURE 1 The *Lumbricus terrestris* midden and general soil (not to scale)

non-middened pair, the 'general' soil without a midden was sampled using the soil corer at a 30-cm distance from the midden (Figure 1).

2.2.2 | Clay mineral analysis

One pair of middened and non-middened were analysed. Soil samples were prepared for X-ray diffraction (XRD) analysis on the <2 μm fraction with clay mineral identification and quantification carried out using the NEWMOD II modelling approach as previously described (Kemp, Ellis, Mounteney, & Kender, 2016).

2.2.3 | Aggregate stability analysis

Soil samples were collected from nine selected plots in the Spring for laboratory aggregate stability assessments, using the rapid wetting test that generates a mean weight diameter (MWD). The nine plots were triplicate conditions: nil (no organic amendment), residual compost or FYM (previously applied at 3.5 kgC ha^{-1} between 2013 and 2016). Interpretation was based on the stability categories: very unstable (<0.4 mm), unstable (0.4–0.8 mm), medium (0.8–1.2 mm) and stable (>1.2 mm) (Le Bissonnais, 1996). Oven dried (40°C), sieved (5 mm) and weighed (5.0 ± 0.01 g) soil aggregates were gently immersed into deionised water (50 ml) for 10 min. The saturated soil was transferred to a 50 μm sieve and immersed in methylated spirit and gently agitated in a twisting motion at a 3 cm amplitude for 10 cycles. After air-drying the samples were oven dried (105°C) and weighed before being passed through a sieve column (order of mesh size: $W_{2,000}$, $W_{1,000}$, W_{500}, W_{200}, W_{100} and W_{50} μm + the non-mesh bottom collector tin: Wcollector) by gently shaking for 30 s. The mass (g) of each size fraction was recorded. Aggregate stability was expressed as the MWD, which is the sum of the mass fraction remaining in each sieve multiplied by the mean aperture of the adjacent mesh:

$$MWD = ([5-2]/2)W_{2,000} + ([2+1]/2)W_{1,000} + ([1+0.5]/2)W_{500} + ([0.5+0.2]/2)W_{200} + ([0.2+0.1]/2)W_{100} + ([0.1+0.05]/2)W_{50} + (0.05/2) \times (W_3 + W_c).$$

2.3 | Soil sampling for X-ray computed tomography (CT scanning)

The high concentration of flints in this soil precluded large soil core collection. For the large soil clod analysis, a 14 cm fork was used to collect a soil block of middened and paired general soil (30 cm from the midden) from nine plots, the day before analysis. The vertical orientation was maintained, and the block broken by hand along natural aggregates to make a 10 cm × 10 cm × 5 cm clod. This was placed in a small plastic box (11 cm × 11 cm × 8 cm) for transportation and remained undisturbed for analysis (i.e., clods were analysed in the box). For the soil aggregates, a small hand fork was used to collect a small <5-cm depth soil block of middened and paired general soil (30 cm from the midden) from 30 plots. The vertical orientation was maintained, and the block broken by hand along natural aggregates to make a 2 cm × 2 cm aggregate. Three aggregates were packed into 50 ml centrifuge tubes for transportation and remained undisturbed for analysis (i.e., clods were analysed in the tubes).

2.3.1 | CT scanning

CT scanning was performed using a phoenix v|tome|x m 240 kV scanner (GE sensing and Inspection Technologies). For the soil clods this was set at 160 kV and 200 μA, for the soil aggregates it was set at 140 kV and 120 μA. Detector timing was 250 ms, with 2,898 radiograph images (2014 × 2024 pixel) being collected over a 360° rotation in the scanner. Scan spatial resolution was 42 μm for the clods and 18 μm for the aggregates, scan time was 12 min.

2.3.2 | Image processing

Image processing analysis was performed on the raw grey-scale images using ImageJ 1.44 (http://rsbweb.nih.gov/ij/). Each clod image was cropped to a 51 mm × 51 mm × 13.7 mm (800 pixels × 800 pixels × 215 pixels) area and each aggregate was cropped to 19.1 mm × 19.1 mm × 19.1 mm (300 pixels × 300 pixels × 300 pixels) to exclude the outside edge and edge effects. A median filter (radius two pixels) was used to remove noise but maintain borders. To separate pores from the matrix, the results of different threshold settings were visually compared to raw greyscale images. The Otsu global automatic threshold algorithm was selected for the optimum analysis of all samples based on a balanced result between over or under segmentation of the pores from the raw images. After application, the resulting binary images were inverted so that the pores were recoloured to black before analysis. These binary images were analysed using the Analyse Particles tool as previously described (Helliwell, Miller, Whalley, Mooney, & Sturrock, 2014), which calculates each individual pore size and shape.

2.4 | Invertebrate feeding activity

Bait-lamina strips (Terra Protecta GmbH) were used. These are 12-cm long PVC strips that contain 16 round holes containing bait that are inserted vertically into the ground, with a target first bait depth of 0.5 cm and total depth of 8 cm. Briefly, one strip was inserted into the underlying soil of a midden, with five middens studied per plot ($n = 9$) and each midden paired with a strip inserted 30 cm from the midden in the general soil. After 3 weeks, when approximately half the bait had been eaten (as recommended by the manufacturer), the strips ($n = 90$) were collected to determine the percentage of bait points within each strip that had been consumed.

2.5 | Crop yields

Plots were harvested using a Sampo 2010 plot combine over an area of 9 m × 2 m from the centre of each plot (undisturbed by soil sampling). Moisture content was assessed, and yields were expressed at 85% dry matter.

2.6 | *L. terrestris* counts

As previously described (Stroud, Irons, Watts, & Whitmore, 2016), a 1 m^2 square quadrat was used and *L. terrestris* middens counted within 4 m^2 in each experimental plot, for every plot ($n = 75$), totalling an assessment area of 300 m^2. The diameter of 100 middens randomly distributed across the experiment were measured using a tape measure, treating the middens as approximately circular. We did not measure oblong shaped middens. These data were used to calculate the area of the soil surface covered by *L. terrestris* middens.

2.7 | Statistical analysis

Genstat (18th edition; VSN International Ltd.) was used to perform the statistical analyses. General analysis of variance was used with the following parameters: Block: block/plot/middened, treatments = Middened × residual organic matter (meaning previous 2013–2016 compost or FYM amendments). Crop yields and midden counts were assessed using the following parameters: Block/plot, treatments = residual organic matter. The residual graphs were checked to meet the normality assumption and the clod porosity and circularity required log transformation to meet the normality assumption. *t* Tests were used to assess the farmer's earthworm data. Differences obtained at levels $p \leq .05$ were reported as significant.

3 | RESULTS

3.1 | Community science with BASE-UK farmers

Middens covered an average of 21% of the soil surface, ranging from 5 to 41% per participant's field ($n = 9$). There was a significant difference ($p = .03$) in earthworm counts with 225 ± 25 earthworm m^2 associated with middens and 150 ± 25 earthworm m^2 in the general (non-middened) soil patches. Photographs of earthworms indicated

TABLE 1 Comparison of the field soils using XRD analysis of <2 μm fraction to determine clay mineralogy

	Proportion of clay minerals in <2 μm fraction (%)					
Field soil	Illite	Vermiculite	Kaolinite	Smectite/ vermiculite	Nature of interlayered species	Non-clays identified in <2 μm fraction
Middened soil	53	3	23	21	*R*0 50% Sm	Quartz, K-feldspar, plagioclase, goethite, lepidocrocite
General soil	58	3	23	16	*R*0 50% Sm	Quartz, K-feldspar, plagioclase, goethite

Abbreviation: XRD, X-ray diffraction.

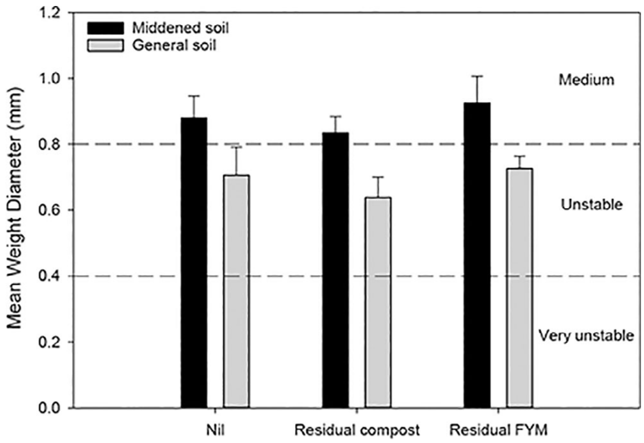

FIGURE 2 Comparison of the aggregate stability determined using the rapid wetting test (crustability). There were significant differences ($p < .05$) between middened and general soil, there were no significant differences between the treatments (nil, residual compost or FYM treatments). FYM, farmyard manure

the populations were dominated by juvenile earthworms and adult endogeic *Allolobophora chlorotica*.

3.2 | Clay mineralogy of the soils from the scientific field experiment

XRD analyses of the clay (<2 μm) fraction of the middened and general soil patches are both predominantly composed of illite with subordinate amounts of kaolinite and smectite/vermiculite and traces of vermiculite (Table 1).

3.3 | Aggregate stability of the soils from the scientific field experiment

The middened soil was significantly ($p = .004$) more stable than the general soil (Figure 2), with middened soil categorised as 'medium' compared to the general soil which was categorised as 'unstable'. There was no significant difference in aggregate stability linked to residual organic amendments ($p = .82$) or types of organic amendment ($p = .98$).

3.4 | CT scanning of the soils from the scientific field experiment

There were significant differences between the middened soil and general soil clods for porosity ($p = .04$), but not pore shape (circularity), $p = .08$ (Table 2). There were no significant differences ($p = .89$, $p = .09$) for either of these soil parameters and residual organic matter amendments (Table 2). There were significant differences between the middened soil and general soil aggregates for porosity ($p < .001$) but not pore shape ($p = .968$) (Table 3). There were no significant differences ($p = .16$, $p = .38$) for either of these soil parameters and residual FYM (Table 3).

3.5 | Invertebrate feeding activity on the scientific field experiment

There was significantly ($p < .001$) more feeding activity in the middened soil compared to the general soil (Figure 3). There was a significant difference in feeding activity linked to residual organic amendments ($p = .03$), but not types of organic amendment ($p = .98$).

3.6 | Spring bean yields on the scientific field experiment

There was no correlation ($p > .1$) between plot yields and midden counts. There was no significant difference in crop yields linked to residual organic amendments ($p = .138$), with a grand mean of 2.79 ± 0.08 t beans ha^{-1}.

3.7 | Midden distribution on the scientific field experiment

Middens covered 5% of the soil surface, ranging from 0.5 to 13% per plot ($n = 75$). The average midden diameter was 7.23 ± 2.6 cm (*SD*). There was no significant difference ($p > .05$) in midden counts linked to residual organic amendments, with 3.6 ± 0.3 middens m^2 on FYM, 2.8 ± 0.3 middens m^2 on compost and 3.1 ± 0.3 middens m^2 on control (no amendment) plots.

TABLE 2 Comparison of the porosity and pore shape of the soil clods (resolution 42 μm) and statistical significance (*p* < .05*) with ± *SE*

Field soil Plot treatment	Midden Nil	General Nil	Midden Residual FYM	General Residual FYM	Midden Residual compost	General Residual compost	Middened *p* Value	Middened × residual organic matter *p* Value
% Porosity	15.9 ± 0.56	18.6 ± 4.6	18.6 ± 3.4	13.3 ± 3.3	23.7 ± 2.56	15.9 ± 5.4	.04*	.89
Circularity	0.78 ± 0.01	0.81 ± 0.00	0.78 ± 0.01	0.78 ± 0.01	0.77 ± 0.11	0.78 ± 0.00	.08	.09

Abbreviation: FYM, farmyard manure.

TABLE 3 Comparison of the porosity and pore shape of the soil aggregates (resolution 18 μm) and statistical significance (*p* < .05*) with ± *SE*

Soil pair Plot treatment	Midden Nil	General Nil	Midden Residual FYM	General Residual FYM	Midden vs. non-midden *p* Value	FYM × midden *p* Value
% Porosity	11.3 ± 2.4	7.5 ± 0.9	16.3 ± 2.3	7.6 ± 0.9	<0.001*	0.16
Circularity	0.82 ± 0.01	0.81 ± 0.01	0.82 ± 0.02	0.83 ± 0.01	0.97	0.38

Abbreviation: FYM, farmyard manure.

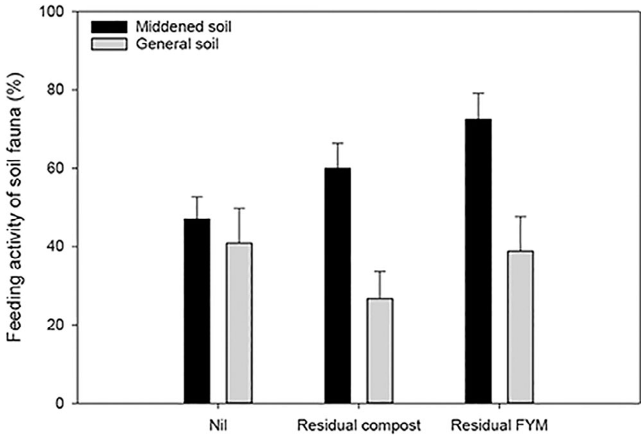

FIGURE 3 Comparison of the feeding activity of invertebrates. There were significant differences (*p* < .05) between middened and general soil and between the treatments (nil, residual compost and FYM) suggesting a legacy effect. FYM, farmyard manure

4 | DISCUSSION

We suggested a community science activity to farmers interested in 'scientific advances in earthworm science' that resulted in farmers sharing images of middens covering 5–42% of the soil surface in their fields. These farmers have adopted minimum soil disturbance, residue cover on the surface and rotations (conservation agriculture) that would explain abundance of middens which is in agreement with the scientific literature. In terms of timescales, scientists have shown that there is an immediate response by *L. terrestris* to the application of surface residues, with significant redistribution into middens detected within days to a density of 30 middens per m^2 (McTavish & Murphy, 2022). This is dependent on soils management, abundances ranging from 0 to 3 middens per m^2 under conventional tillage compared to 28 middens per m^2 under no-till (Simonsen, Posner, Rosemeyer, & Baldock, 2010). Middens can cover around 25% of the soil surface in no-tillage management systems indicating the potential impact of *L. terrestris* earthworms at field scales (Subler & Kirsch, 1998). Middens are persistent, for example, at high abundances (28–30 middens per m^2) midden arrangement has been found to be consistent within a growing season (2 months–1 year) (Grigoropoulou & Butt, 2010).

Middened soil was studied by the farmers and had significantly more earthworms than the general soil, therefore, the null hypothesis can be rejected with evidence that middened soil has significantly more earthworms compared to the general soil. The photographs of the earthworms indicated an abundance of adult *A. chlorotica* and juvenile earthworms were associated within the middens, in agreement with our research on middens from Rothamsted field trials (Stroud, Irons, Carter, et al., 2016). Scientists have found that middens are hotspots of earthworm, mesofauna and microbe activity (Butt & Lowe, 2007; Hamilton & Sillman, 1989), and for the first time, we demonstrate that UK farmers can also detect this phenomenon in their fields. Science–farming partnerships are important because heuristics (to learn or discover for yourself) is associated with sustained pro-environmental behaviours (Mills et al., 2017). This is linked to the development of pro-environmental values shaped using information circulating in social learning networks (Coughenour, 2003). The quality of information circulating in those networks is therefore important because farmer-to-farmer learning is key to developing soil conservation practices (Skaalsveen, Ingram, & Urquhart, 2020; Wheeler & Lobley, 2021). Research has shown that the abundance of middens is positively correlated to soil health measurements because anecic earthworms stimulate soil biology and engineer soil physical properties (e.g., aeration and drainage) (Jemison, Kersbergen, Majewski, & Brinton, 2019). The time investment by farmers into midden surveying suggests that an advance in earthworm monitoring could be based on middens, rather than random sampling of earthworms in soil pits which is inherently problematic at field scales (Hodson et al., 2021).

Unfortunately, there are few opportunities for establishing long-term farming–science partnerships because DEFRA dismantled the agricultural knowledge and information system (Sutherland et al., 2013).

In terms of the scientific literature, there are mixed definitions of earthworm activities: the drilosphere was originally described as the area within 2 mm of burrow walls (e.g., Figure 1) whereas middens were described separately as a vermisphere, but the drilosphere can mean middens and the porosphere (earthworm derived pores) (Sharma, Chandra, & Chandra, 2018). Detailed characterisation determined that both the middened and general soil from the scientific field experiment is dominated by 2:1 clay minerals (Table 1) and these minerals are responsive to biological aggregate formation and stabilisation mechanisms (Denef & Six, 2005). The middened soil (soil directly under a midden, Figure 1) had significantly higher aggregate stability than the general soil (Figure 2), which would be classified as 'medium' compared to 'unstable' using the slaking test. Therefore, we reject our null hypothesis with evidence that middened soil has significantly different aggregate stability compared to the general soil. This result helps to explain why changing from conventional tillage to no-tillage practices leads to a recovery in aggregate stability (Kibblewhite et al., 2008). It has been previously reported that *L. terrestris* earthworms improve aggregation and form middens which promote the decay and incorporation of organic residues in soils (Shipitalo & Le Bayon, 2004),

The general role of earthworms in aggregate formation has been known for 75 years, with epigeics having little effect compared to endogeic and anecic earthworms (Hallam & Hodson, 2020). Our field-derived results are in agreement with laboratory earthworm studies using intensively processed soils (250 μm–8 mm sieved and repacked soil microcosms) which reported earthworms stimulate the formation of macroaggregates when plant residues are applied to the soil surface (Frazão, de Goede, Capowiez, & Pulleman, 2019). These laboratory studies artificially distributed plant residues on the soil surface, but *L. terrestris* shapes the spatial patterns of plant residue distribution (McTavish & Murphy, 2022). Laboratory studies have detected fast aggregation with significant differences measured within 22 days (Bossuyt, Six, & Hendrix, 2006), 40 days (Hallam & Hodson, 2020) and 61 days (Frazão et al., 2019) depending on earthworm densities. These laboratory results help to explain the context of our results. The farm has been managed under conventional tillage for hundreds of years and has a history of poor aggregate stability which is detrimental to spring cropping (Avery & Catt, 1995). The scientific field trial was recently converted to no-tillage management, meaning the general soil was 'no-tillage' and there was only a significant improvement in aggregate stability directly associated with middened soil patches made by *L. terrestris*.

The architecture of the soil, that is, the spaces or porosity where almost all soil microbiology and chemistry occurs could be influenced by *L. terrestris* mediated plant residue distributions. Detailed analyses of undisturbed soil clods and aggregates analysed at 42 and 18 μm resolution respectively indicated a significant difference in the porosity of middened soils compared to the general soil (Tables 2 and 3). Therefore, we reject our null hypothesis with evidence that middened soil is significantly different compared to the general soil at scales relevant to water storage, flow and gas diffusion (<42 μm). These results are in agreement with laboratory earthworm microcosm studies where topsoil (2.5–10 cm) porosity was significantly higher in treatments with surface-applied residues (Frazão et al., 2019).

The redistribution of surface plant residues by *L. terrestris* could influence below-ground feeding activities by influencing the microclimate and food resources. Middened soil had significantly more invertebrate feeding activity than the general soil (Figure 3). These bait strips are principally consumed by earthworms (van Gestel, Kruidenier, & Berg, 2003), which is in agreement with middens as hotspots for the earthworm community (Butt & Lowe, 2007; Stroud, Irons, Carter, et al., 2016). Therefore, we reject our null hypothesis, with evidence that middened soil has significantly different faunal feeding activity compared to the general soil. These results are in agreement with laboratory and field research which demonstrated that middened areas are hotspots of decomposition (McTavish & Murphy, 2022).

The previous organic matter amendments cultivated into the soil and hypothesised to improve soil physical properties mediated by soil fauna (Whitmore et al., 2017) had no significant (p > .05) residual effect on aggregate stability, porosity or crop productivity (Tables 1–3, Figures 1–3). Previously, the annual amendments of FYM influenced the distribution of middens (Stroud, Irons, Watts, et al., 2016). Here, there were no significant (p > .05) differences in midden abundances, although there was significantly higher (Figure 2) invertebrate feeding activity. We found no evidence for legacy effects on the soil physical structure from the previous additions of organic matter amendments, which is notable because our study is focussed on the rain-impacted surface soil layer (0–5 cm). The top 4 cm or the rain-impacted layer is considered the most appropriate depth the examine soil aggregate–carbon interactions (Loveland & Webb, 2003).

5 | CONCLUSION

Piles of surface litter (midden), collected and maintained by *L. terrestris* earthworms cover up to 13% of the soil surface of the studied field, and up to 42% in farmer's fields. These middened soil patches had improved aggregate stability, porosity, invertebrate feeding activity and higher numbers of earthworms compared to the general (non-middened) soil patches. Our findings highlight the importance of considering middens when surveying soil quality and health in arable systems. Overlooking or deliberately avoiding midden sampling could lead to incorrect conclusions about earthworm functions and the recovery of soil from over-cultivation.

AUTHOR CONTRIBUTIONS

J.L.S. conceived the ideas. J.L.S., C.J.S., S.J.K. and I.P.C. designed the methodology. I.D., C.J.S., S.J.K., J.L.S. and participating farmers collected the data. J.L.S. analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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