Received: 23 May 2023 | Revised: 31 October 2023 | Accepted: 4 November 2023
DOI: 10.1111/sum.12985

Soil Use and Management
WILEY

RESEARCH PAPER

The effect of organic matter amendments on soil surface stability in conventionally cultivated arable fields

Jacqueline L. Stroud[1] | **Simon J. Kemp**[2] | **Craig J. Sturrock**[3]

[1]School of Life Sciences, University of Warwick, Coventry, UK
[2]British Geological Survey, Environmental Science Centre, Keyworth, UK
[3]Hounsfield Facility, School of Biosciences, Sutton Bonington Campus, University of Nottingham, Leicestershire, UK

Correspondence
Jacqueline L. Stroud, School of Life Sciences, University of Warwick, Coventry, CV4 7AL, UK, UK.
Email: jacqueline.stroud@warwick.ac.uk

Funding information
Natural Environment Research Council

Abstract

In this study, new and traditional organic wastes (green waste compost, farmyard manure (FYM), anaerobic digestate or straw) were ploughed into an arable field experiment at a range of rates (1–3 t C ha^{-1}) and under spring and winter cropping rotations for 5 years. The stability of the soil surface structure (<5 cm) was assessed in Years 3, 4 and 5 to guide the use of organic wastes in arable field management. Aggregate stability was determined by immersing each soil sample in water (fast-wetting test, relevance to summer storms) and measuring the size distribution of the aggregates (mean weight diameter, MWD). The MWD value was compared with the different classes of aggregate stability (very stable, stable, medium, unstable or very unstable) to classify each result. All the arable field samples were classified as unstable, and there were no significant differences ($p > .05$) in MWD after any treatment. Potentially, this approach is too imprecise to detect differences, so pore-scale analyses using CT scanning were used. There were no significant differences in porosity or pore shape (features associated with microbial activity) between the control and organic waste treatments. The results contradicted published data from the Broadbalk experiment (established in 1843), which was the basis for this study, so its soils were studied to understand this discrepancy. Broadbalk soils were classified as unstable, including soils treated with annual FYM applications. Instead, we found a significant relationship between MWD and clay content and previous interpretations had not taken this variable (23%–39% clay content) texture into consideration. In conclusion, to achieve a stable soil surface structure, a 150% improvement in aggregate stability would be needed here and ploughing in organic wastes was not a successful management approach on these arable field experiments.

KEYWORDS
aggregate stability, organic matter, plough, soil health

1 | INTRODUCTION

The maintenance of stable soil surface conditions is important to the conservation of soil. The soil surface (<5 cm) is vulnerable to summer storms, particularly when rain falls on (initially) dry soil aggregates. Dry aggregates are subject to fast wetting and internal pressures from entrapped air. If the aggregate is not strong enough to withstand these internal stresses, then it quickly disintegrates (slakes). A secondary process of mechanical raindrop impact can further breakdown aggregates. A laboratory test known as the fast-wetting method was developed to describe slaking behaviours and classify soil stabilities ranging from very unstable to very stable aggregate behaviours (Le Bissonnais, 1996).

A survey of surface (<5 cm) farmland soils in England and Wales was conducted using Le Bissonnais (1996) fast-wetting test and detected widespread soil surface instability under plough-based production systems (Watts & Whitmore, 2004). This helped to explain widespread flooding after stormy weather, which was originally thought to have been caused by saturated subsoil conditions. Intensive soil cultivations continue to dominate crop production systems in England (Townsend et al., 2016). Interventions which deliver stable soil surface conditions in plough-based production systems are needed.

The application of farmyard manure (FYM) to arable soils has been a management practice for many centuries and is associated with a 'stabilized soil' (Williams, 1977). Research on the Broadbalk Wheat Experiment, which has been in ploughed-arable production since 1843, detected that both FYM and straw-amended plots had improved mean weight diameter (MWD) using the Yoder (1936) fast-wetting method (Blair et al., 2006). There are new sources of organic matter for field applications because of the EU 2020 Landfill Directive, with both green waste compost and anaerobic digestate being recycled back to the land. The aim of this work was to provide management guidance for the use of organic waste applications (rate, type) to achieve the benefit of stable soil surface conditions in plough-based production systems.

2 | MATERIALS AND METHODS

2.1 | Fosters field experiment

The field research was located at Rothamsted Research Farm (51.82 N and 0.37 W), which has a temperate climate in the South of England. The Fosters field has been used for conventional arable agriculture for >100 years (e-RA, 2018a). The soil is characterized as a flinty silty clay loam of the Batcombe series, with total C 1.6% (LECO) and pH 6.99 measured prior to starting the field experiment. The field experiment was started in 2012 and was a 220-plot complete randomized block design comparing organic matter types, rates and inorganic nitrogen rates in an arable crop rotation (full details reported elsewhere (Whitmore et al., 2017)). Each plot was 9 m × 6 m in size. Organic matter types included anaerobic digestate (fibre portion of a brassica waste and maize-fed digester), green waste compost, cattle FYM or straw (from the previous crop in the rotation), and their chemical properties have been reported elsewhere (Sizmur et al., 2017). These amendments were applied by hand each Autumn and ploughed in using a 3-furrow plough to ca. 23 cm every year.

The sampling strategy was deployed to identify the type and rate of organic amendment which produced stable aggregate behaviours (>1.3 mm size distribution of the aggregates or MWD, Table 2 (Le Bissonnais, 1996)). Soil samples were collected from selected plots in May 2015, 2016 and 2017 (Table 1) as the test is relevant to summer storm behaviour. Different features of the experiment were explored: Year 3: (i) the effect of organic amendments to each other and no organic amendment under winter wheat and (ii) the effect of different rates of cattle FYM (0–3.5 t C ha^{-1}) and nitrogen (80–220 kg N ha^{-1}) under winter wheat. Year 4: (iii) the effect of spring barley or winter wheat cropping and organic amendments, repeated in Year 5: (iv) the effect of organic amendments under winter wheat. Additionally, soil samples were taken from selected plots from the Fosters long-term experiment, which is a 40-plot randomized block design arable experiment. Treatments studied were the permanent bare fallow (since 1960, four replicate plots) and permanent grass (since 1948, four replicate plots).

2.2 | Broadbalk field experiment

The experiment started in 1843 and is located at Rothamsted Research, Hertfordshire (51.8081 N:0.3752 W). The soil is classified as a Chromic Luvisol, consisting of a flinty clay loam to silty clay loam. This research was performed in 2017 on sections 0, 1, 6 and 9 (Table 3), which include three closely related soil types: Typical Batcombe Series (sections 0, 1 and 6), Heavy Batcombe Series (patches on sections 0 and 1) and Charity-Notley Series (section 9), with a broad-ranging clay content (19.6%–38.7%) (Watts et al., 2006). A detailed description and soil type map are available elsewhere (Goulding et al., 2000).

The Broadbalk Wheat Experiment comprises a 4.8-hectare, conventionally managed, tile-drained site that is conventionally cultivated, that is, presently ploughed to 20–23 cm, power harrowed, rolled and drilled. All plots in this study (ca. 6 m × 23 m except for section 0 which is shorter and FYM plots which are narrower) were under monoculture winter wheat (sections 0, 1, 6 and 9). Treatments studied included the control (Nil), chemical fertilizer combinations or two FYM combinations (Table 3). All sections were fallowed periodically between 1926–1967, and sections 0 and 6 have been fallowed at times since then. Sections 1 and 9 are in continuous wheat, Section 0 is the only section where straw is returned (since 1987), and section 6 was in a rotation for a few years (1968–1977) and is the only section where spring or summer fungicides have not been used (since 1985). The experiment was established long before statistical experimental designs were developed. So, the sections and treatments

TABLE 1 Selected plots studied on Fosters field experiment.

Year	Experiment duration	Crop	Number of plots studied	Inorganic fertilizer rate Kg N ha^{-1}	Plot replicates per organic treatment	Organic matter treatment	Rate of C t C ha^{-1}
2015	3 years	Winter wheat (cv. Crusoe)	18	220	2	1) Anaerobic digestate 1b) Anaerobic digestate plus oil seed rape (OSR) straw 2) Green waste compost 2b) Green waste compost plus OSR straw 3) Cattle FYM 3b) Cattle FYM plus OSR straw 4) OSR straw 5) No organic treatment (control)	3.5
2015	3 years	Winter wheat (cv. Crusoe)	16	80–220	2	1) Cattle FYM 2) No organic treatment (control)	1–3.5
2016	4 years	Winter wheat (cv. Crusoe)	18	220	4	1) Anaerobic digestate 2) Green waste compost 3) Cattle FYM 4) Oat straw 5) No organic treatment (control)	2.5
2016	4 years	Spring barley (cv. Tipple)	18	190	4	1) Anaerobic digestate 2) Green waste compost 3) Cattle FYM 4) Wheat straw 5) No organic treatment	2.5
2017	5 years	Winter wheat (cv. Crusoe)	18	220	4	1) Anaerobic digestate 2) Green waste compost 3) Cattle FYM 4) Wheat straw 5) No organic amendment	2.5

are parallel to each other, not randomized, blocked or replicated. The soil sampling design was two samples per plot collected in May 2017. Additionally, the grass, woodland and managed woodland (stubbed) areas on the Broadbalk Wilderness were sampled as being undisturbed by tillage since 1882. Supplementary data (soil texture) were obtained from e-RA and Rothamsted Annual Reports (e-RA, 2018b).

2.3 | Soil sampling

Following the protocol to study surface soil physical properties (Watts & Whitmore, 2004), a soil corer (75 mm diameter steel ring) was used to collect soil samples to 50 mm depth from selected plots and placed into individual plastic boxes for transportation to the laboratory.

2.4 | Measurement of aggregate stability (MWD)

Oven-dried (40°C), sieved (5 mm) and weighed (5.0 ± 0.01 g, W1) soil aggregates were gently immersed into deionized 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 (Watts & Whitmore, 2004). After air-drying the samples were oven-dried (105 °C) and weighed (W2) before being passed through a sieve column (order of mesh size: W_{2000}, W_{1000}, W_{500}, W_{200}, W_{100} and W_{50} μm + Wcollector) by gently shaking for 30 s. The mass (g) of each size fraction was recorded. The results were 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:

$$\begin{aligned}\mathrm{MWD} = {} & ((5-2)/2)\,W_{2000},+((2+1)/2)\,W_{1000},\\ & +((1+0.5)/2)\,W_{500},+((0.5+0.2)/2)\,W_{200},\\ & +((0.2+0.1)/2)\,W_{100}+((0.1+0.05)/2\,W_{50}\\ & +(0.05/2)\ \mathrm{x}\ \left(W1-W2+W_{c}\right)\end{aligned}$$

An analytical replicate was included in every batch of 12 samples for quality control of the procedure, with an acceptable 6.7 ± 1.2% difference. The MWD obtained was interpreted in relation to the five categories of crustability (Table 2) (Le Bissonnais, 1996).

TABLE 2 Stability categories based on Le Bissonnais (1996).

Aggregate stability, mean weight diameter (mm)	Category
<0.4	Very unstable
0.4–0.8	Unstable
0.8–1.3	Medium
1.3–2	Stable
>2	Very stable

2.5 | Measurement of total C

All the Fosters soil samples collected from (i) and (ii) and the controls, and the Broadbalk field samples were finely ground and analysed for total C using LECO (**TruMac Combustion Analyser**). An analytical replicate was performed for every 10 samples for quality control of the procedure, with an acceptable 0.5 ± 0.18% difference.

2.6 | Analysis of clay minerals

Soil samples from the Fosters arable experiment, permanent fallow and grass plots were used. From Broadbalk, selected soil samples ($n = 12$) were analysed for clay mineralogy: FYM + N3 (strip 2.1), Nil (Strip 3) and N1 + 2 + 1PKMg (Strip 18) from each continuous wheat section (0, 1, 6 and 9) to span all three soil types (Typical Batcombe, Heavy Batcombe and Charity-Notley series soils) present. Samples were prepared for X-ray diffraction analysis on the <2-micron fraction with quantification carried out using the NEWMOD II modelling approach as described previously (Kemp et al., 2016).

2.7 | Soil sampling from fosters field for X-ray computed tomography

Twelve plots cultivated under winter wheat (cv. Crusoe) were chosen for analysis in 2016. These were the controls (no organic amendment) at nil ($n = 2$ plots) and at the recommended fertilizer rate of 190 kg N ha^{-1} ($n = 2$ plots) and the organic amended plots at the recommended fertilizer rate (as above), anaerobic digestate ($n = 2$), compost ($n = 2$), FYM ($n = 2$) or oat straw ($n = 2$). The high number of flints in this soil preclude soil core collection, thus large soil clods were analysed. One large (20 cm × 20 cm) soil block per plot was collected pre-harvest using a 14 cm wide gardening fork the day before analysis. The vertical orientation was maintained, and the block was broken by hand (along natural aggregates) to make a ca. 10 cm × 10 cm × 8 cm clod. This was placed in a small plastic box (11 cm × 11 cm × 10 cm) for transportation and remained undisturbed for analysis (i.e., clods were analysed in the box).

2.7.1 | X-ray CT

X-ray computed tomography (X-ray CT) was performed using a phoenix v|tome|x m 240 kV scanner (GE sensing and Inspection Technologies), set at 160 kV energy and 200 μA current. Detector timing was 250 ms, with collection of 2898 radiograph images (2014 × 2024 px) over a 360° rotation of the clod in the scanner using the 'FAST scan' mode (e.g., continuous sample rotation with no image averaging applied). Scan spatial resolution and total acquisition time were 42 microns and 12 min, respectively.

2.7.2 | Image processing

Image processing analysis was performed on the raw greyscale images using ImageJ 1.44 software (http://rsbweb.nih.gov/ij/). Each clod image was cropped to a 44.8 × 44.8 mm × 19.2 mm (700 × 700 × 301 pixels) area to exclude the outside edge and edge effects. A 2D median filter (radius = 2 pixels) was used to remove noise but maintain borders. To separate pores from the matrix, the results of different threshold settings were visually compared with raw greyscale images. The otsu global automatic threshold algorithm was selected for the optimum analysis of all 12 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 prior to analysis. These binary images (301 images per sample) were analysed using the 'Analyse Particles' tool as described previously (Helliwell et al., 2014), which calculates the size and shape of each individual pore (ca. 100, 000 pores per image stack). Quantitative assessments for the number of pores, total area of pores, average size of pores, porosity (%), perimeter, circularity and feret diameter were determined. Feret is the longest dimension of a pore in these 2D sections, the perimeter is the distance in pixels around each pore, and the area is the number of pixels contained within.

TABLE 3 Selected plots studied on Broadbalk field experiment: organic farmyard manure (FYM). N as single applications: N1, N2, N3, N4, N5 and N6 are 48, 96, 144, 192, 240 and 288 kg N ha^{-1} as ammonium nitrate.

Section	Section management	22	21	3	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
0	*Continuous wheat with straw return*	FYM N2	FYM	NIL		N1	N2	N3	N4	N4	N4	N1+	N4	N4	N5	N6	N1+	N1+	N1+
												3+1					4+1	2+1	1+1
					(P)	(P)	(P)	(P)	(P)		P	(P)	P	P	(P)	(P)	P	P	
					K	K	K	K	K			K	K	K*	K	K	K	K	K
					Mg	Mg	Mg	Mg	Mg		Mg	Mg2		Mg	Mg	Mg	Mg	Mg	Mg
1	*Continuous wheat*	FYM N2	FYM	NIL		N1	N2	N3	N4	N4	N4	N1+	N4	N4	N5	N6	N1+	N1+	N1+
												3+1					4+1	2+1	1+1
					(P)	(P)	(P)	(P)	(P)		P	(P)	P	P	(P)	(P)	P	P	
					K	K	K	K	K			K	K	K*	K	K	K	K	K
					Mg	Mg	Mg	Mg	Mg		Mg	Mg2		Mg	Mg	Mg	Mg	Mg	Mg
6	*Continuous wheat with no Spring or Summer fungicides*	FYM N2	FYM	NIL		N1	N2	N3	N4	N4	N4	N1+	N4	N4	N5	N6	N1+	N1+	N1+
												3+1					4+1	2+1	1+1
					(P)	(P)	(P)	(P)	(P)		P	(P)	P	P	(P)	(P)	P	P	
					K	K	K	K	K			K	K	K*	K	K	K	K	K
					Mg	Mg	Mg	Mg	Mg		Mg	Mg2		Mg	Mg	Mg	Mg	Mg	Mg
9	*Continuous wheat*	FYM N2	FYM	NIL		N1	N2	N3	N4	N4	N4	N1+	N4	N4	N5	N6	N1+	N1+	N1+
												3+1					4+1	2+1	1+1
					(P)	(P)	(P)	(P)	(P)		P	(P)	P	P	(P)	(P)	P	P	
					K	K	K	K	K			K	K	K*	K	K	K	K	K
					Mg	Mg	Mg	Mg	Mg		Mg	Mg2		Mg	Mg	Mg	Mg	Mg	Mg
Wilder-ness	*Woodland*																		
	Mown grass																		
	Managed woodland (stubbed)																		

Note: The + indicates a split application of N. P is triple superphosphate, Mg is kieserite. K is potassium sulphate, and K* is potassium chloride. Elements in brackets were applied until 2000.

2.8 | Statistical analysis

Genstat (18th addition, VSN International Ltd., UK) was used to perform the statistical analyses. For the MWD assessments, General ANOVA (Analysis of Variance) was used. For (i) and (iv), the following parameters were applied: Block: Block/Plot, Treatments = split/omtypes, where split was a two-factor category comparing the presence/absence of organic amendment and omtypes were each organic amendment (anaerobic digestate, compost, FYM or straw). The residual graphs were checked to meet the normality assumption, and the MWD required log transformation to meet the normality assumption. For (ii), the following parameters were used: Block: Block/Plot, Treatments = split/Nrates/omrates, where N rates was a four-factor category comparing the different rates of N-applied. The residual graphs were checked to meet the normality assumption, and the MWD required log transformation. For (iii), the following parameters were used: Block: Block/Plot, Treatments = crop*(split/omtypes). The residual graphs were checked to meet the normality assumption, and the MWD required log transformation. For total C for (i), the following parameters were used: Block: Block/Plot, Treatments = split/omtype and for (ii), the following parameters were used: Block: Block/Plot, Treatments = split. The residual graphs were checked to meet the normality assumption. Linear regression analysis was used to assess the relationship between MWD and soil carbon and texture from the Broadbalk Wheat Experiment. For the X-ray CT assessments, General ANOVA was used with the following parameters: Block = Block/Plot/Slice, Treatments = split/Nrate/omtypes, where split and N rate were two-factor categories comparing the presence/absence of organic amendment or N rate, respectively. The 'Slice' means each CT image in the stack, om types included each organic amendment (anaerobic digestate, compost, FYM or oat straw). The residual graphs were checked to meet the normality assumption, and for four parameters (average size, perimeter, feret and area) required log transformation to meet the normality assumption. Feret is the longest dimension of a pore in these 2D sections, the perimeter is the distance in pixels around each pore, and the area is the number of pixels contained within. Differences obtained at levels $p \leq .05$ were reported as significant.

3 | RESULTS

3.1 | (i): The effect of single and mixed organic amendments on mean weight diameter in Year 3

There was no significant effect ($F_{(1,22)} = 0.37$, $p > .05$) from the annual application of organic amendments for 3 years on Fosters field (Figure 1). The treated and untreated soils had values of <0.8 mm, which is characterized as unstable (Table 2). The permanent fallow was categorized as unstable (0.42 ± 0.04 mm), and the permanent grass plots were stable (2.23 ± 0.34 mm).

3.2 | (ii): The effect of rates of FYM and inorganic N additions on MWD in Year 3

There was no significant effect ($F_{(1,7)} = 0.07$, $p > .05$) (Figure 2) from the annual application of FYM for 3 years on Fosters field, and all arable samples were categorized as unstable.

3.3 | (iii): The effect of spring barley or winter wheat cropping and organic amendments on MWD in Year 4

There was no significant effect ($F_{(1,25)} = 0.99$, $p > .05$) from the crop system and annual application of organic amendments for 4 years on Fosters field (Figure 3). The MWD of the untreated soil was 0.46 ± 0.08 mm, in comparison with the organic amended soils, which was 0.48 ± 0.03 mm, both of which are in the unstable category. The permanent fallow plots were categorized as unstable (0.58 ± 0.01 mm), which contrasted to the very stable (2.32 ± 0.05 mm) permanent grass plots.

3.4 | (iv): The effect of single organic amendments on mean weight diameter in Year 5

There was no significant effect ($F_{(1,14)} = 1.07$, $p > .05$) from the annual application of organic amendments for 5 years on aggregate stability (Figure 4) and were categorized as unstable.

3.5 | Broadbalk field

The FYM treatment samples ($n = 18$) had MWD values ranging between 0.35 and 0.89 mm (min – max), with a median value of 0.6 mm (Unstable, Figure S1). The nil treatment samples ($n = 8$) had MWD values ranging between 0.33 and 0.52 mm (min – max), with a median value of 0.43 mm (unstable). The inorganic fertilizer samples ($n = 120$) had MWD values 0.29–1.39 mm (min – max), with a median value of 0.57 mm (unstable). The wilderness samples ($n = 4$) had MWD values ranging between 2.49 and 3.00 mm (min – max), with a median value of 2.84 mm (stable).

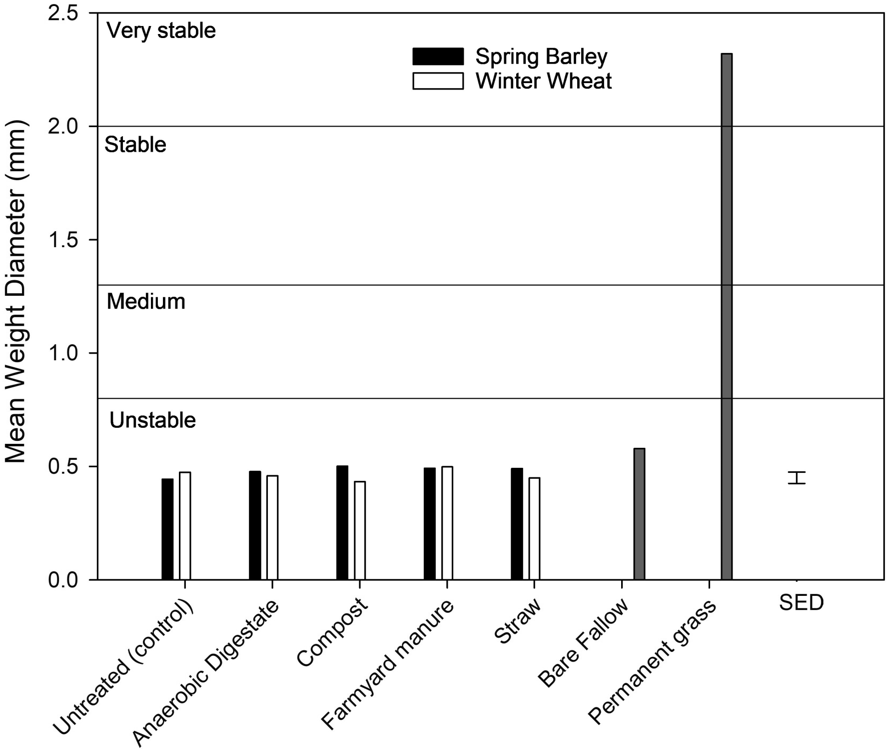

FIGURE 1 Effect of 3.5 tonnes C ha^{-1} organic wastes on soil surface MWD in Year 3, the lack of significance is indicated by ± S.E.D. standard error of the differences. The black fill colour is the Fosters arable field treatments. The grey fill colours are the neighbouring Fosters fallow and permanent grass treatments providing a minimum and maximum MWD context for this field.

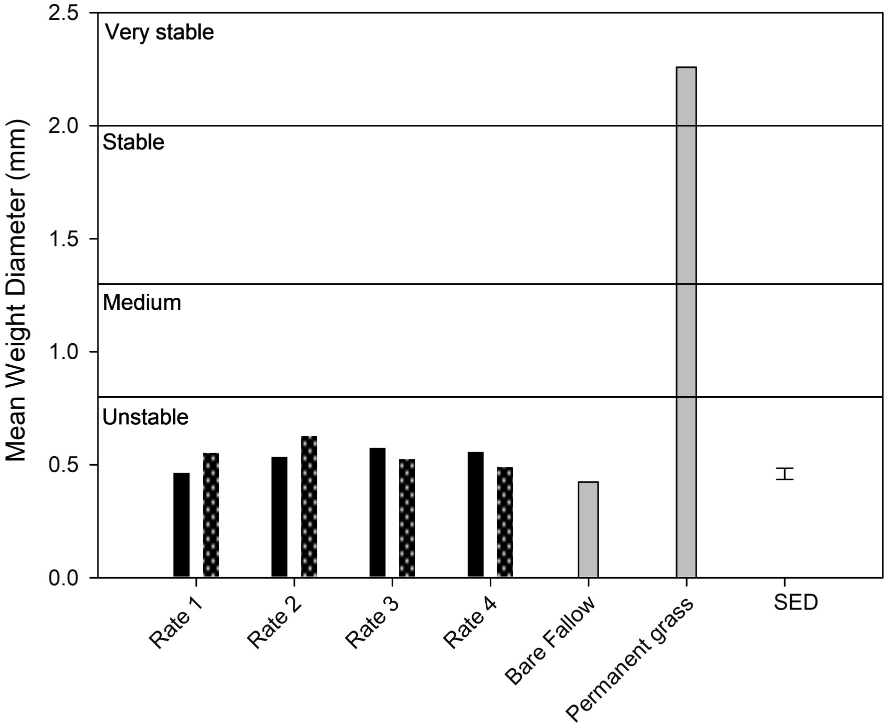

FIGURE 2 Effects of different rates of farmyard manure (FYM) on surface MWD in Year 3, with ± S.E.D. standard error of the differences. The black fill colour represents the control (no FYM) and the spotted fill colour is the treatment (FYM). The FYM Rate 1 was 1 t C ha^{-1}, Rate 2 was 1.75 t C ha^{-1}, Rate 3 was 2.5 t C ha^{-1}, and Rate 4 was 3.5 t C ha^{-1} and Nitrogen rate range: Rate 1 was 80 kg N ha^{-1}, Rate 2 was 150 kg N ha^{-1}, Rate 3 was 190 kg N ha^{-1}, and Rate 4 was 220 kg N ha^{-1}. The FYM Rate 1 was 1 t C ha^{-1}, Rate 2 was 1.75 t C ha^{-1}, Rate 3 was 2.5 t C ha^{-1}, and Rate 4 was 3.5 t C ha^{-1}. The grey fill colours are the neighbouring Fosters fallow and permanent grass treatments providing a minimum and maximum MWD context for this field.

Selected plots on section 1 have been previously studied and interpreted as FYM having a stabilizing effect (Blair et al., 2006; Williams, 1977). Focussing on section 1 (Figure 5), there was no relationship between soil carbon (%) and MWD [($r = .04$, $n = 37$, $p = .8$, F-test of the correlation)](Figure 5). There was a statistically

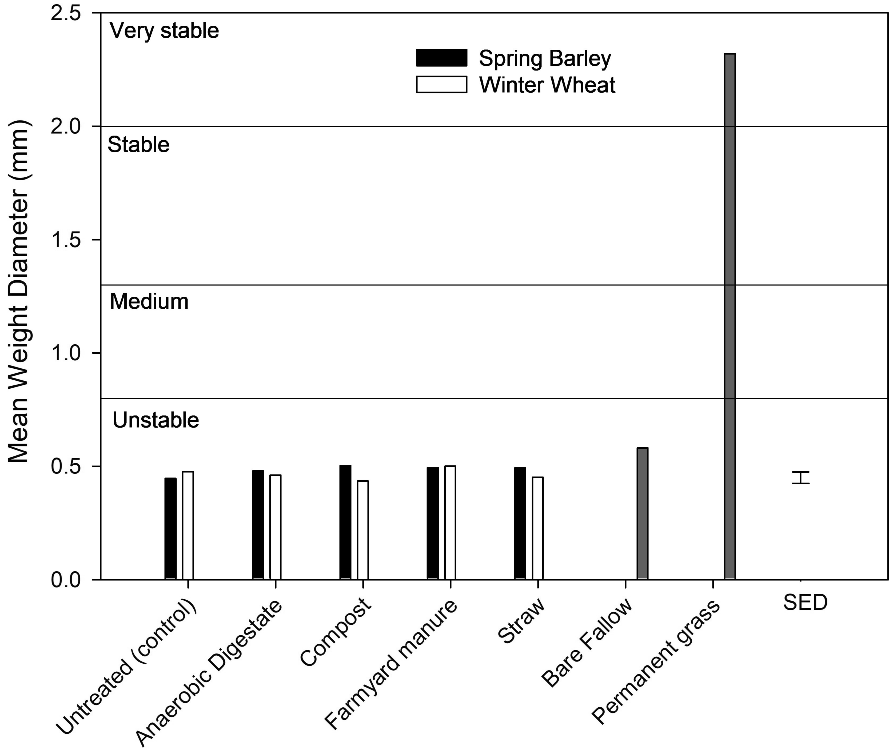

FIGURE 3 Effect of 2.5 tonnes C ha^{-1} organic wastes on soil surface MWD in Year 4, with ± S.E.D. standard error of the differences indicating lack of significance. The white and black fill colours are spring barley and winter wheat, respectively, from the Fosters arable field treatments. The grey fill colours are the neighbouring Fosters fallow, and permanent grass treatments providing a minimum and maximum MWD context for this field.

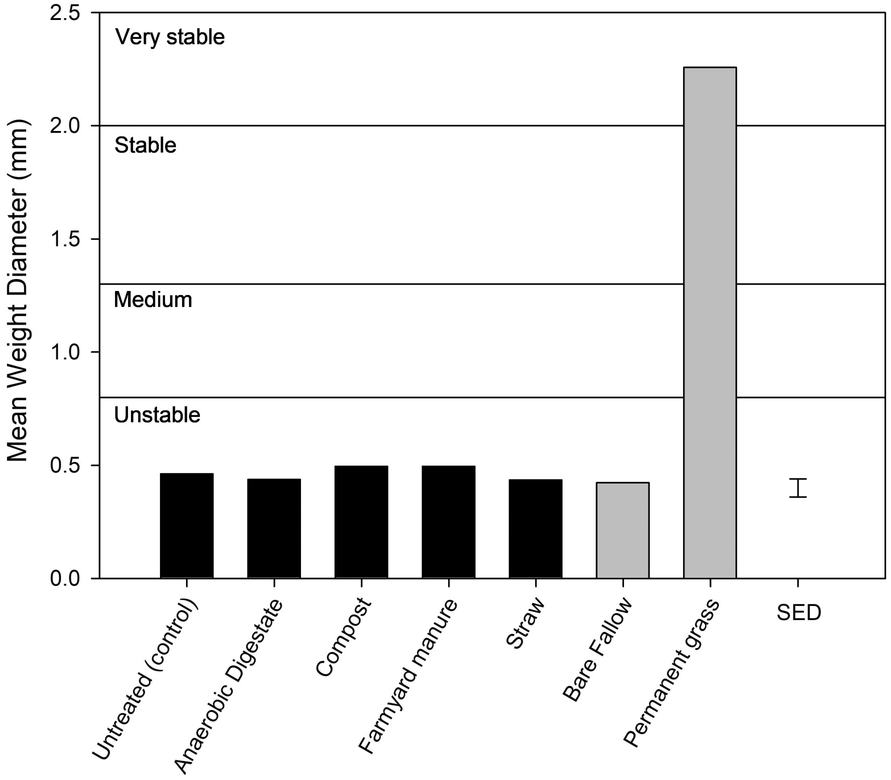

FIGURE 4 Effect of 2.5 tonnes C ha^{-1} organic wastes on soil surface MWD in Year 5, with ± S.E.D. standard error of the differences indicating lack of significance. The black fill colour is the Fosters arable field. The grey fill colours are the neighbouring Fosters fallow and permanent grass treatments providing a minimum and maximum MWD context for this field.

significant relationship between clay content (%) and MWD [($r = .63$, $n = 37$, $p < 0.01$, F-test of the correlation)]. One arable field sample ($n = 146$) from Section 1, Strip 18, was categorized as stable (>1.3 mm). The soil texture was checked, and this plot has the highest clay content (39%) on Broadbalk.

3.6 | Soil total carbon (surface <50 mm)

There was no significant effect ($F_{(1,7)} = 1.13$, $p > .05$) on total organic carbon from the application of organic amendments on Fosters field. The total soil carbon was 1.41 ± 0.186% for the untreated soils, in comparison with

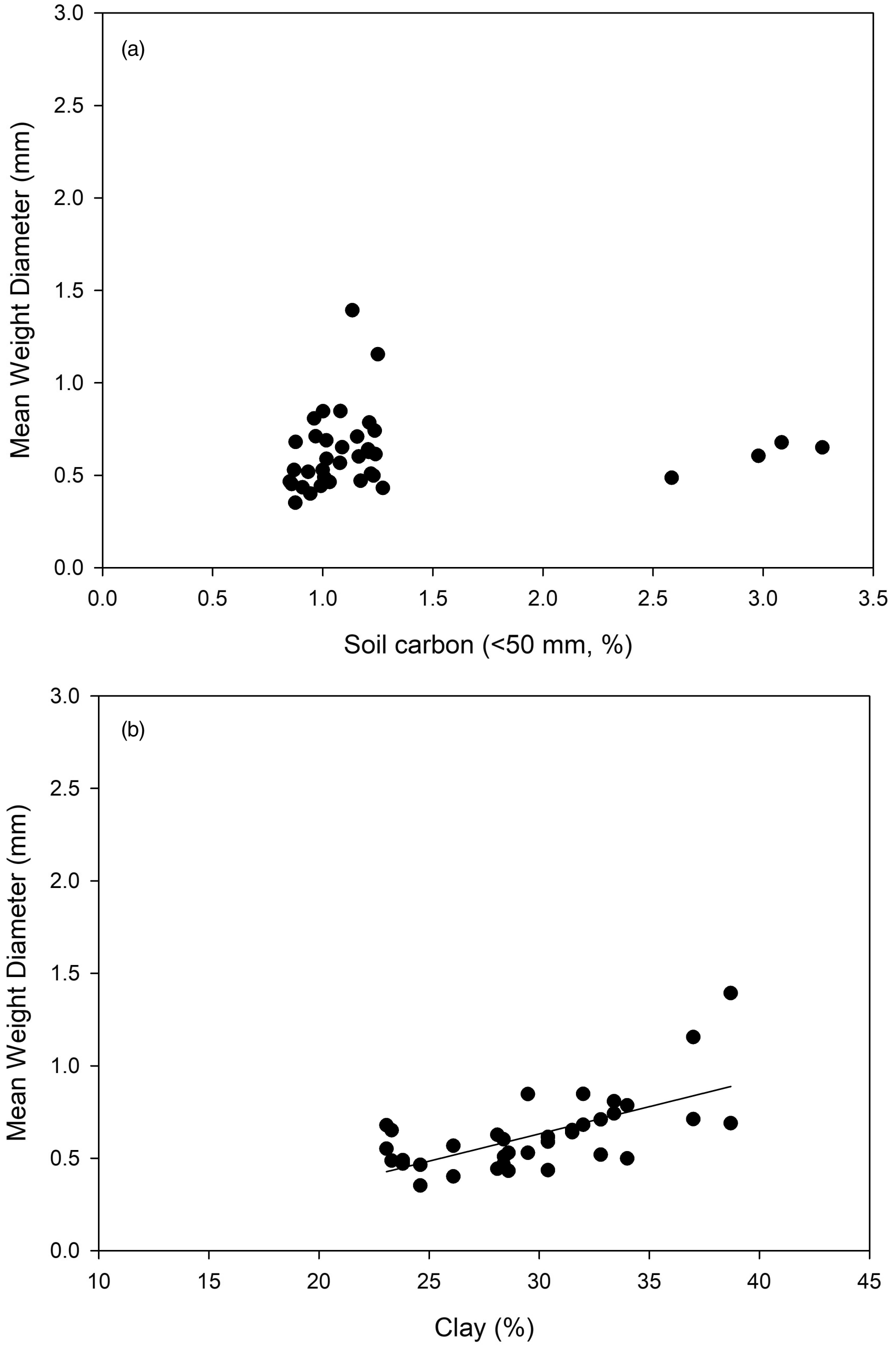

FIGURE 5 Broadbalk wheat experiment section 1 (a) No relationship between soil carbon and mean weight diameters (MWD) (b) significant relationship between clay content and MWD.

the organic matter amended soils, which ranged between 1.41% and 2.06% (Table S1). There was no significant effect ($F_{(1,13)} = 1.78$, $p > .05$) on total organic carbon from the application of FYM at different rates. The total soil carbon was 1.41 ± 0.04% for the untreated soils, in comparison with the FYM amended soils with a value of 1.43 ± 0.03%. In comparison, the permanent fallow plots' soil carbon value was 1.5 ± 0.05% compared with the grass 3.8 ± 0.5%.

In terms of Broadbalk field, the nil treatment samples ($n = 8$) had a Total C median value of 1.01%. The FYM treatment samples ($n = 18$) had Total C median value of 2.5%. The inorganic fertilizer samples ($n = 120$) had Total C median value 1.17%. The wilderness samples ($n = 4$) had Total C values ranging between 5.91 and 8.27% (min – max), with a median value of 6%.

3.7 | Clay mineralogy

XRD analyses of Fosters soils suggest that the clay (<2 μm) fraction is predominantly composed of illite with subordinate amounts of kaolinite and smectite/vermiculite and traces of vermiculite (Table S2). Similarly, XRD analyses of Broadbalk soils suggest that the clay (<0.2 μm) fraction is dominantly composed of illite, kaolinite and smectite/

TABLE 4 Statistical significance (<0.05*) of the soil structural parameters from X-ray CT scans of the organic matter amended soils compared with non-amended soils on Fosters field.

Parameter	*p-value*
Frequency	.013*
Total area	.330
Average size (log transformed)	.071
% Area	.399
Perimeter (log transformed)	.063
Circularity	.105
Feret diameter (log transformed)	.053

vermiculite (Table S3), irrespective of soil types across the field.

3.8 | X-ray CT

There were no significant differences between the untreated soils in comparison with the organic amended soils for either porosity ($F_{(1,5)} = 0.85$, $p > .05$) or pore shape (circularity) ($F_{(1,5)} = 3.92$, $p > .05$) (Table 4). The organic matter amended soils were associated with an increase in the number of small pores ($F_{(1,5)} = 14.17$, $p < 0.05$).

4 | DISCUSSION

The performance of soil surface aggregates from a tilled-arable production system was studied here as widespread arable soil surface instability has been previously reported (Watts & Whitmore, 2004). Slaking is the main mechanism of rainfall-induced breakdown of aggregates, and persistent instability has implications for erosion, pollution transport and runoff/flooding (Shi et al., 2017). The highest UK 60-minute rainfall record is 92 mm, recorded in Maidenhead, Berkshire, England (MetOffice, 2023). The depth of the soil surface which interacts with intense rainfall (50–90 mm hr^{-1}) can range between 1.5 and 5.7 cm depth depending on soil aggregate stability and soil slope (Sharpley, 1985). The beneficial effect of soil organic matter on aggregate stability is confined to <4 cm (Unger, 1995) and <5 cm (Shirani et al., 2002) in tilled production systems, indicating that soil sampling depth is important for interpreting aggregate stability (Loveland & Webb, 2003). Little is known about the influence of green waste compost and anaerobic digestate on soil aggregate stability, but these new sources of organic waste materials improve soil physical properties in the topsoil (Bhogal et al., 2018; WRAP, 2015).

There was no improvement in soil aggregate stability after 3 years (Figures 1 and 2), 4 years (Figure 3) or 5 years of annual organic matter applications (Figure 4), spanning different application rates, types of amendments or spring/winter cropping scenarios. Fosters arable soil has a MWD of <0.8 mm for all samples, which is classified as unstable (Table 2). This is the same category as the long-term bare fallow on this field (Figures 1–4). The Fosters soil is capable of existing as very stable aggregates under permanent grass (Figures 1–4), indicating that the measurement of MWD and the soil type is not the cause of these findings. This is further confirmed by clay mineralogical analysis identifying that the field soil is dominated by 2:1 clays (Table 2), which are responsive to aggregation mediated by soil biology (Denef & Six, 2005). Porosity and pore shape have been linked to microbial activity (Helliwell et al., 2014), and pore scale analyses (42 microns) were performed; however, no significant differences were detected (Table 4). There were no significant differences in surface (<5 cm) carbon (Table S1), indicating that there was no change in food availability for soil organisms at the soil surface. These findings are in agreement with previous findings on this field: no measurable response by the microbial community in the top 10 cm soil, or earthworm community (surveyed to 20 cm depth) to the organic amendments (Whitmore et al., 2017). The organic matter amended soils were associated with an increase in the number of small pores, which could be linked to the drying pattern of the soil caused by the increase in crop yields (Whitmore et al., 2017).

These experiments on Fosters fields were developed based on previous findings from the adjacent Broadbalk experiment where the application of FYM were reported to significantly improve 'soil physical fertility' (Blair et al., 2006; Williams, 1977). The clay mineralogy of both fields could be a potential factor influencing macro-aggregation, but both field soils are dominated by 2:1 clay minerals (Tables S2 and S3). The results from this study agree with published studies that the wilderness areas have high structural stability (Blair et al., 2006). However, it was reported that organic manures 'stabilized' soil based on a water slaking test on selected plots ($n = 6$) on section 1 (Williams, 1977). Similarly, soil stability was measured using the Yoder (wet sieving) method on topsoil (0–10 cm) from selected plots ($n = 10$) on sections 0 and 1 and found FYM increased MWD (Blair et al., 2006). We did not find evidence that FYM applications result in stable soils (Figure S1, Figure 5a). Instead, we detected a significant effect of clay content (%) on MWD in section 1 (Figure 5b), a variable which was not measured by previous authors and likely confounds previous interpretations of MWD data.

Our aim was to generate guidance for farmers to achieve the benefit of stable soil surface in ploughed production systems. To achieve a MWD >1.3 mm, a 150% improvement in aggregate stability would likely be needed on the experimental field trials studied here. Whilst the literature indicates that organic matter applications improve aggregate stability, the size of the effect is not in this order of magnitude. For example, a statistically significant 10% improvement in aggregate stability resulting from the application of organic wastes is detected in laboratory studies, achieving a MWD of 0.85 mm (Saygın et al., 2023). In the field, FYM applications can lead to rapid <2 years improvements in aggregate stability, achieving a MWD of 0.75 mm (Shirani et al., 2002). The effect of organic waste on aggregate stability in surface soils (<5 cm) from 120 farmland soils from England and Wales was reported as small with values ranging between MWD 0.8–1 mm (Watts & Whitmore, 2004; Whitmore et al., 2017).

It is important to contribute to sustainable soil management guidance because research has indicated that many farmers perceive that runoff is perceived to be caused by others, or uncontrollable, leaving soil erosion problems unresolved (Ingram et al., 2010). Many authors do not differentiate between statistical significance and practical significance: an unstable soil surface poses risks of erosion, pollution transport and runoff/flooding. This could help to explain why there are widespread unstable surface soils in arable production systems (Watts & Whitmore, 2004) and the perception that this is uncontrollable. Our results indicated that the time and labour invested in 'stabilizing' organic matter amendments did not achieve the desired benefit, and highlight that other strategies are needed.

5 | CONCLUSION

Annual organic matter amendments (1–3 t C ha^{-1}, FYM, compost, anaerobic digestate or straw) ploughed into an arable field did not increase surface structural stability (measured by MWD) over 5 years. The soil surface was characterized as unstable throughout this study. The basis of this study was based on published findings from the Broadbalk experiment which suggested FYM amendments are stabilizing. A comprehensive re-evaluation of the Broadbalk wheat experiment identified the soil surface is unstable, and previous interpretations based on section 1 data were likely confounded by the highly variable clay content (23%–39%).

ACKNOWLEDGEMENTS

The authors would like to thank A. Whitmore and C. Watts for access to the Fosters field experiment, M. Raynaud, A. Moss and J. Carter for technical support and R. White for statistical analysis support at Rothamsted Research. J.L.S. was supported by a NERC fellowship (NE/N019253/1). S.J.K. publishes with the permission of the Director (BGS, UKRI). The Rothamsted Long-term Experiments National Capability (LTE-NC) is supported by the UK BBSRC (Biotechnology and Biological Sciences Research Council, BBS/E/C/000 J0300) and the Lawes Agricultural Trust.

CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

REFERENCES

Bhogal, A., Nicholson, F. A., Rollett, A., Taylor, M., Litterick, A., Whittingham, M. J., & Williams, J. R. (2018). Improvements in the quality of agricultural soils following organic material additions depend on both the quantity and quality of the materials applied. *Frontiers in Sustainable Food Systems*, *2*.

Blair, N., Faulkner, R. D., Till, A. R., & Poulton, P. R. (2006). Long-term management impacts on soil C, N and physical fertility: Part I: Broadbalk experiment. *Soil and Tillage Research*, *91*, 30–38.

Denef, K., & Six, J. (2005). Clay mineralogy determines the importance of biological versus abiotic processes for macroaggregate formation and stabilization. *European Journal of Soil Science*, *56*, 469–479.

e-RA. (2018a). *Electronic Rothamsted archive*. Lawes agricultural trust and Rothamsted research data e-RA database. www.era.rothamsted.ac.uk/Met

e-RA 2018b. *Electronic Rothamsted Archive*. Lawes Agricultural Trust and Rothamsted Research e-RA database. www.era.rothamsted.ac.uk/Met.

Goulding, K. W. T., Poulton, P. R., Webster, C. P., & Howe, M. T. (2000). Nitrate leaching from the Broadbalk wheat experiment. *Rothamsted, UK, as Influenced by Fertilizer and Manure Inputs and the Weather.*, *16*, 244–250.

Helliwell, J. R., Miller, A. J., Whalley, W. R., Mooney, S. J., & Sturrock, C. J. (2014). Quantifying the impact of microbes on soil structural development and behaviour in wet soils. *Soil Biology and Biochemistry*, *74*, 138–147.

Ingram, J., Fry, P., & Mathieu, A. (2010). Revealing different understandings of soil held by scientists and farmers in the context of soil protection and management. *Land Use Policy*, *27*, 51–60.

Kemp, S. J., Ellis, M. A., Mounteney, I., & Kender, S. (2016). Palaeoclimatic implications of high-resolution clay mineral assemblages preceding and across the onset of the Palaeocene–Eocene thermal maximum, North Sea Basin. *Clay Minerals*, *51*, 793–813.

Le Bissonnais, Y. (1996). Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *European Journal of Soil Science*, *47*, 425–437.

Loveland, P., & Webb, J. (2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: A review. *Soil and Tillage Research*, *70*, 1–18.

MetOffice 2023. *UK rainfall records for short durations*. In, https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-extremes. www.metoffice.gov.uk

Saygın, F., Alaboz, P., Dengiz, O., & Şenol, H. (2023). The effect of organic waste applications on soil aggregation and soil organic carbon fractions. *Communications in Soil Science and Plant Analysis*, *54*, 1644–1656.

Sharpley, A. N. (1985). Depth of surface soil-runoff interaction as affected by rainfall, soil slope, and management. *Soil Science Society of America Journal*, *49*, 1010–1015.

Shi, P., Thorlacius, S., Keller, T., Keller, M., & Schulin, R. (2017). Soil aggregate breakdown in a field experiment with different rainfall intensities and initial soil water contents. *European Journal of Soil Science*, *68*, 853–863.

Shirani, H., Hajabbasi, M. A., Afyuni, M., & Hemmat, A. (2002). Effects of farmyard manure and tillage systems on soil physical properties and corn yield in Central Iran. *Soil and Tillage Research*, *68*, 101–108.

Sizmur, T., Martin, E., Wagner, K., Parmentier, E., Watts, C., & Whitmore, A. P. (2017). Milled cereal straw accelerates earthworm (*Lumbricus terrestris*) growth more than selected organic amendments. *Applied Soil Ecology*, *113*, 166–177.

Townsend, T. J., Ramsden, S. J., & Wilson, P. (2016). How do we cultivate in England? Tillage practices in crop production systems. *Soil Use and Management*, *32*, 106–117.

Unger, P. W. (1995). Organic matter and water-stable aggregate distribution in ridge-tilled surface soil. *Soil Science Society of America Journal*, *59*, 1141–1145.

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

Watts, C. W., & Whitmore, A. P. (2004). *Critical levels of soil organic carbon in surface soils in relation to soil stability, function and infiltration* (p. 21). DEFRA final project report SP0519. In.

Whitmore, A. P., Watts, C. W., Stroud, J. L., Sizmur, T., Ebrahim, S., Harris, J. A., Ritz, K., Wallace, P., White, E., Stobart, R., McKenzie, B., & Thallon, G. (2017). *Improvement of soil structure and crop yield by adding organic matter to soil*. AHDB Project Report No. 576 In.

Williams, R. J. B. (1977). *Effects of management and manuring on physical properties of some Rothamsted and Woburn soils*. In Rothamsted Experimental Station Report for 1970 - Part 2 (pp. 37–54).

WRAP. (2015). *Field experiments for quality Digestate and compost in agriculture – WP1 report*. In. DC-Agri.

Yoder, R. E. (1936). A direct method of aggregate analysis of soils and a study of the physical nature of erosion Losses1. *Agronomy Journal*, *28*, 337–351.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Stroud, J. L., Kemp, S. J., & Sturrock, C. J. (2023). The effect of organic matter amendments on soil surface stability in conventionally cultivated arable fields. *Soil Use and Management*, *00*, 1–12. https://doi.org/10.1111/sum.12985