Triaxial Testing to Determine the Effect of Soil Type and Organic Carbon Content on Soil Consolidation and Shear Deformation Characteristics

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The purpose of this paper is to determine the effect of soil type and organic matter on the deformation characteristics of soil. We used triaxial testing to measure both the consolidation and shear deformation of soil. The novel application of this method was applied to soils from two experiments: on a clay loam and a sandy loam. The clay loam soil was from the long-term Broadbalk Experiment at Rothamsted Research, UK, where contrasting treatments had been applied since 1843. The sandy loam soil was from a straw incorporation experiment started in 1986. The clay loam soil from selected treatments from the Broadbalk Experiment had large difference in soil organic C (SOC) content due to additions of farmyard manure (FYM) or inorganic fertilizers for over 170 yr. There were no detectable differences in SOC or microbial biomass C in the sandy loam soil where straw had been incorporated. In addition to triaxial testing, we assessed soil physical condition with measurements of aggregate stability and aggregate tensile strength. From triaxial tests of the repacked soil, we found that soil type and SOC affected the compression characteristics. We also observed that deformation characteristics are more sensitive to small changes in soil management practices designed to increase the SOC content, than measurements of aggregate tensile strength, friability, or stability. We suggest that measurement of deformation characteristics is a potentially powerful approach for detecting or predicting changes in soil physical conditions as impacted by small changes in SOC content resulting from management practices.

Abbreviations: CSL, critical state line; FYM, farmyard manure; NCL, normal consolidation line; SOC, soil organic C.

Within a given soil type, organic matter management has a large impact on physical behavior. Soils with higher contents of SOC are more stable, have a lower bulk density, and offer a lower resistance to root elongation (Whalley et al., 2007; Matthews et al., 2008). Addition of organic materials may also have the potential to increase soil C stocks. Thus, there is considerable interest in increasing the SOC content (Powlson et al., 2011b; Powlson et al., 2012). A range of widely differing approaches exists to describe physical behavior of the soil. In this paper, we applied triaxial testing of soil deformation to determine the effect of soil management on its physical behavior using soils that have been managed with the purpose of increasing the SOC. Although triaxial testing has been applied in other contexts, it has rarely been used to quantify soil physical condition in agricultural soils; instead uniaxial compression is frequently used, which appears

to be insensitive to both soil type and management (Keller et al., 2011). For comparison, we also used the most common methods to characterize soil structural condition, namely measurements of aggregate stability and friability.

Uniaxial consolidation (e.g., Baumgartl and Kock, 2004; Zhang et al., 2005; Keller et al., 2011; Gregory et al., 2006) has the benefit that soil characteristics, such as precompression stress and compressibility, can be determined after fitting relatively simple curves to the data, which can be obtained with relative ease. Usually soil pore pressure is not controlled, which affects the shape of the compression curve and restricts the interpretation because effective stress cannot be estimated with any certainty (Tang et al., 2009). Deformation of soil is not merely an increase in soil density but includes the effects of soil shear deformation. An alternative to uniaxial testing is triaxial testing, which differs in two respects: (i) both the radial and axial stresses applied to the soil are controlled and (ii) the pore water pressure is usually either controlled or measured. Although, pore water pressure can be controlled in uniaxial tests (e.g., Cui et al., 2010),

it is not the norm. Triaxial testing allows the effects of both consolidation and shear deformation on soil density (or porosity) to be quantified. Relatively few studies have explored both the consolidation and shear deformation, although exceptions are found in O'Sullivan and Robertson (1996) and Kirby (1991). The critical state model, although little used in agricultural soils, is a potentially powerful tool (see Hettiaratchi and O'Callaghan, 1985 and Kirby, 1991). This approach allows changes in both shear and mean stresses to be related to changes in porosity (Fig. 1). The critical state behavior of soil can be summarized by the normal consolidation line (NCL) and the critical state line (CSL) as follows

$$e = N + \lambda \log(\sigma) \quad (\text{for NCL}) \tag{1}$$

and

$$e = N' + \lambda' \log(\sigma) \quad (\text{for CSL}) \tag{2}$$

where e and σ are the void ratio and mean effective stress, respectively; N and λ are characteristic constants (O'Sullivan and Robertson, 1996). The normal consolidation line (Eq. [1], NCL) is determined under isotropic stress conditions (i.e., in absence of any shear deformation). If at any point, a normally consolidated soil is sheared to the point where deformation occurs at a constant mean stress, the soil will have reached the critical state condition irrespective of whether it is sheared at a constant porosity (Path 3, Fig. 1) in an undrained test or it is allowed to consolidate during shear (Path 2, Fig. 1). The critical state line (Eq. [2], CSL) provides a unique relationship to characterize any given soil, where soil structure is degraded to the extent that only textural pore space exists (Mitchell and Soga, 2005), and in this condition the soil is similar to remolded soil. Equation [2] is the projection of the CSL on to the porosity-mean stress plane (Fig. 1). The NCL and the CSL delineate the boundaries of a family of consolidation curves, which depend on the ratio of shear to mean stress and, thus, identify the range of porosity and mean stress combinations that are permissible in an under-consolidated stable soil.

The stability of soil aggregates subject to wetting and/or mechanical agitation can provide a rapid measure of soil physical and structural conditions. However, a disadvantage is that there is no accepted standard method to measure aggregate stability (Merrington et al., 2006). The use of different methodologies and variations on methodologies has made comparison of data difficult. For the same reason, it has also been difficult to obtain consistent relationships between aggregate stability and other important soil factors such as erodibility and the formation of soil crusts (Amezketa, 1999). Despite these problems, aggregate stability provides a rapid and useful physical index of soil structural condition (Watts and Dexter, 1997). In this work, we use the protocol similar to that developed by Le Bissonnais (1996) to rapidly assess the stability of soil structures.

The tensile strength of soil is widely believed to be a sensitive measure of soil structure (Rogoswki and Kirkham, 1968; Watts and Dexter, 1998). One of the most widely used methods for measuring tensile strength of soil is the indirect tension test. A compressive force is applied across the diameter of a cylinder,
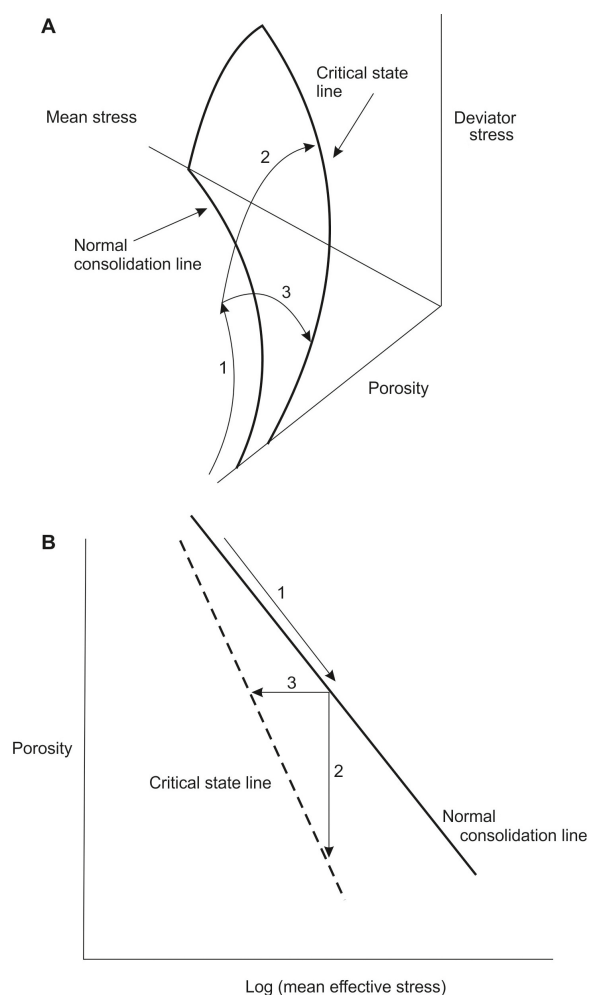

Fig. 1. Normal consolidation line and critical state line (a) of a soil and their projections on the porosity mean stress plane (b). Normal consolidation is shown along Path 1 where the sample is exposed to an isotropic stress. This is sometimes called the isotropic consolidation line or the virgin compression line. Shear deformation Path 2 is a drained test at a constant mean stress while in Path 3 the sample is undrained during shear and at a constant porosity.

sphere, or aggregate-shaped soil sample, which causes a tensile stress within the sample acting at right angles to the direction of the applied force (Rogowski Kirkham, 1968; Dexter, 1975). Failure occurs when a crack appears between the points of loading, and there is a sudden decrease in the force that the soil sample can sustain. As the crack runs through preexisting structural pores, this test is assumed to be highly sensitive to soil structural condition. It is also assumed that the soil failure is brittle, so this approach tends to be used in dry soils. Friability is estimated from the variability of tensile strengths within a population of similar sized samples or aggregates. Friability has also been found to be particularly sensitive to changes in SOC (Watts and Dexter, 1998). Both tensile strength and friability have provided useful insights into soil structure and behavior (Dexter and Watts, 2001).

We investigated the effect of increased SOC on the deformation of repacked soil at the macroscopic scale (core scale). A computer controlled triaxial instrument was used to investigate the normal isotropic consolidation followed by shear deformation until the critical state was achieved. The pressures we apply are within the range normally used in such measurements and relevant to those pressures experienced by soil in the field (e.g., Tang et al., 2009). We also investigated the relationship between the tensile strength and friability of aggregates and soil organic matter. Since soil stability, and in particular the rapid wetting of dry aggregates, is one of the most widely used indicators of the effect of SOC on soil physical condition, this measure was also included. For comparisons, we used two different soils (clay loam and a sandy loam) from long-term experiments both subject to different management practices. In the clay loam, there was a large difference in SOC due to the addition of FYM over 170 yr. In the sandy loam, straw had been incorporated for 26 yr but with limited increase in SOC. An objective of this work was to determine which of these different methods for determining characteristic soil physical behavior was most sensitive to small changes in SOC.

MATERIALS AND METHODS
Soils

To determine the effect of SOC on soil deformation, soil samples with contrasting SOC were collected by using a trowel from the 0- to 10-cm layer. We collected soil samples from two long-term treatments (since 1843) on the Broadbalk wheat experiment: (i) farm yard manure at 35 t ha^{-1} (BroadbalkFYM) and (ii) inorganic fertilizers, including P, K, and Mg, without additional N (BroadbalkPKMg); Na was applied until 1967 and P has been withheld since 2001. Soils from a long-term (since 1986) straw incorporation experiment at Woburn (Far Field) were collected from four treatments. These were a control with no straw incorporation (straw baled and removed) and three treatments where wheat straw was incorporated at either the rate equivalent to the annual straw yield on the site or two times or four times that rate. The annual straw incorporation rates averaged 0, 4, 8, and 16 t ha^{-1}. Field moist samples were kept in polythene bags and immediately transferred to the laboratory and stored at 4°C until further analysis. The moisture content at the time of sampling ranged between 16.4 and 18.1% at Broadbalk and 14.2 and 15.8% at Farfield, Woburn. Subsamples of these field moist soils were used for triaxial testing. The remaining soil was air-dried at room temperature. Aggregates (10–20 mm) were hand-picked from soils air-dried in the laboratory and used for tensile strength measurement. For the stability test (Le Bissonnais method, see below), air-dried soils were sieved to obtain aggregates between 5 and 3.5 mm in diameter (sieve size).

The properties of the soils are summarized in Table 1. The particle size distributions of all the soils were determined by sieving and sedimentation (British Standards, 1975). From here on the soils are referred to with the labels listed in Table 1.

Table 1. Selected properties of the soils used for the study (Whalley et al., 2011, Gregory et al., 2010; Powlson et al., 2011a).

Property	Broadbalk FYM	Broadbalk PKMg	Far Field
Label	B-FYM	B-PKMg	F0 or F4†
Location	Rothamsted Res., Hertfordshire	Rothamsted Res., Hertfordshire	Woburn Exp. Farm, Bedford
Latitude	51.809484	51.809491	52.008238
Longitude	−0.373396	−0.37332	−0.618936
SSEW series‡	Batcombe	Batcombe	Lowlands
U.S. Soil Taxonomy	Paleudalf	Paleudalf	Cumulic Haplumprept
Land use	Arable, cereals, farm yard manure	Arable, cereals, fertilized	Arable, cereals, straw incorporation
Sand (2.0–63 μm), kg kg^{-1}	0.252	0.252	0.655
Silt (63–2 μm), kg kg^{-1}	0.497	0.497	0.232
Clay (<2 μm), kg kg^{-1}	0.252	0.252	0.111
Texture, SSEW class	Clay loam	Clay loam	Sandy loam
Particle density, g cm^{-3}	2.508	2.56	2.65
Water content at which the soils are most compactible g/g	0.25	0.2	
SOC, kg kg^{-1}	**0.031**§	**0.009**	See Table 2 for treatment specific data

† F0 is zero straw incorporation and F4 is four times the annual straw yield (see Table 2).
‡ SSEW, Soil Survey of England and Wales.
§ Bold values measured autumn 2010 (0–23 cm; Powlson et al., 2011a).

Measurement of Consolidation Characteristics

The normal consolidation characteristics and the critical state behavior of the soils were determined on repacked soil samples with a Bishop and Wesley triaxial cell (GDS Instruments, Hook, UK) (see Whalley et al., 2011, 2012a, 2012b). Soils B-FYM, B-PKMg, F0, and F4 were repacked at the water content at which they were collected. However, these water contents were close to those at which the soils were most compactable (Table 1). The soils were packed into a split brass mold 38 mm in diameter and 76 mm tall, in approximately eight layers with an axial pressure of 10 kPa. This procedure was similar to that described by Adams and Wulfsohn (1997). The packed soil cylinder was placed in a latex membrane and mounted on the pedestal of the triaxial compression apparatus as described by Whalley et al. (2011). The pressure of the water surrounding the sample (the cell pressure) and the pressure of the soil water (pore water) were increased from 10 and 0 KPa to 600 and 590 kPa, respectively, over a period of 24 h. This allowed the soil to saturate at an effective stress of 10 kPa. The soil was then subjected to a range of isotropic consolidation pressures to give effective stresses between 10 and 500 kPa. The NCL was determined with several (up to eight) independent tests for each of the soils investigated (Whalley et al., 2011, 2012b). At the maximum consolidation pressure in each test, the soil was subjected to shear deformation by increasing the axial stress relative to the radial stress until deformation continued to occur at a constant mean effective stress. At this point, the critical state had been achieved. In all the cases, the soil was deformed from its cylindrical shape (at the end of normal consolidation) to a barrel shape (at the end of shear deformation at the critical state). With one exception (one test of B-FYM soil), all of the triaxial shear tests were undrained tests and at a constant porosity. The drained shear deformation of one B-FYM sample took place over 24 h and the mean stress was kept constant. The final volume of the soil after testing was obtained by oven-drying the sample at 105°C to determine the mass of water and solid, which were then converted to volumes.

Measurement of Tensile Strength and Friability of Soil Aggregates

The tensile strength and friability of soil aggregates were determined with the procedure described by Dexter and Watts (2001). Thirty aggregates of 10 to 20 mm were air-dried by oven-drying at 40°C for 12 h before the tests. The aggregate tensile strength, Y was calculated from the equation:

$$Y = 0.576 \frac{P}{D^2} \qquad [3]$$

where P is the applied force and D is the mean diameter of the aggregates (mm).

In this study, we used digital calipers to measure each aggregate with the mean of the longest (D_x), intermediate (D_y), and smallest (D_z) diameters of each aggregate used to estimate the average diameter D_0. The D_0 was normalized with the aggregate mass M to give D,

$$D = D_0 \left(\frac{M}{M_0} \right)^{1/3} \qquad [4]$$

where M_0 is the average mass of 30 aggregates. It was assumed that all aggregates from a particular sample had a similar density.

The tensile strength of soil from a given treatment was expressed as the mean of all the tensile strengths of 30 aggregates. The friability was determined by the equation:

$$F_1 = \frac{\sigma_y}{Y_0} \qquad [5]$$

where Y_0 and σ_Y were the mean and standard deviation of measured values of tensile strength Y.

Measurement of Aggregate Stability

The stability of aggregates was measured after fast wetting of dry aggregates using a technique similar to that described by Le Bissonnais (1996). Rapid wetting was chosen because it is the simplest and quickest test, and it is considered to be highly sensitive at detecting differences due to changes in soil management practices. For this test, 5 g of air-dried soil (3.5–5 mm) were gently immersed in 50 mL of deionized water for 10 min. Excess water was removed with a pipette, and the soil gently wet-sieved by hand in methylated spirit. The mass of each aggregate fraction (from sieve sizes 2, 1, 0.5, 0.2, 0.1, and 0.05 mm) was recorded, and the results were expressed as mean weight diameter (MWD) of aggregates (Van Bavel, 1949).

Determination of Organic Carbon and Microbial Biomass Carbon

Soil organic C was determined on samples collected in autumn of 2012 from the long-term straw incorporation experiment at Woburn. Soils were prepared for analysis as described by Powlson et al. (2011a). In each treatment, 10 to 15 soil cores were taken by hand from each of three plots to a depth of 23 cm using a 2-cm diam. auger. The soils were air-dried before milling (<2 mm) and subsampling for analysis. Total C was determined on a finely milled subsample using a LECO CN combustion analyzer. Carbonate–C was determined by treatment with hydrochloric acid and measurement of evolved CO_2 as described by Kalembasa and Jenkinson (1973). Total organic C was determined as the difference between total-C and carbonate-C. The organic C contents of the soils collected from the other sites (Table 1) were determined with the same method (Powlson et al., 2011a).

Biomass C was determined by the fumigation extraction method (Vance et al., 1987). Field moist samples (<2 mm and adjusted to 40% saturation) were preincubated at 25°C in the dark for 10 d. Three subsamples of soil each containing 50 g were then extracted without further treatment with 200 ml of 0.5 M K_2SO_4 solution. Another three subsamples were chloroform-fumigated in a desiccator and kept in the dark at 25°C for 24 h before extracting with 0.5 M K_2SO_4 solution. Organic C in the filtered extracts was measured using a wet chemical ultra-violet oxidation system

Table 2. Tensile strength, friability of aggregates, and organic C content in bulk soil.

Soil	Properties of aggregates			Organic C content	Biomass C
	Tensile strength	Friability	Mean weight diameter		
	kPa		mm	kg kg^{-1}	mg kg^{-1}
Rothamsted Broadbalk					
B-FYM†	141.4 ± 7.5‡	0.57 ± 0.02	0.476 ± 0.002	**0.031**§	463 ± 41
B-PKMg	140.0 ± 4.6	0.51 ± 0.01	0.366 ± 0.009	**0.009**	175 ± 3
LSD at 0.05	24.5	0.05	0.028	–	113.5
P value	0.88	0.04	< 0.001	–	0.002
Sandy loam with straw incorporated at the rates:					
No straw (F0)	138.5 ± 20.5	0.39 ± 0.03	0.37 ± 0.04	0.009 ± 0.001	152 ± 15
annual straw yield	148.4 ± 12.3	0.45 ± 0.07	0.36 ± 0.02	0.011 ± 0.001	168 ± 6
Two times annual straw yield (F2)	140.1 ± 11.9	0.36 ± 0.04	0.40 ± 0.03	0.012 ± 0.001	165 ± 18
Four times annual straw yield (F4)	124.6 ± 6.2	0.44 ± 0.03	0.39 ± 0.03	0.012 ± 0.001	192 ± 0.4
LSD at 0.05	44.7	0.15	0.09	0.003	39.2
P value	0.681	0.510	0.778	0.406	0.197

† FYM, farmyard manure.

‡ Mean values followed by standard error within each treatment.

§ Bold values are from Powlson et al. (2011a).

(Shimadzu). The microbial biomass C was calculated from the difference between extractable organic C from fumigated and unfumigated samples as described by Vance et al. (1987).

Statistical Analysis

The experimental design was determined by the existing field experiments at Rothamsted.

Statistical analysis was either by analysis of variance or linear regression using GenStat V16. Grouped regression was used to test for differences between compression characteristics.

RESULTS
Soils and Organic Matter Contents

The annual addition of FYM at 35 t ha^{-1} since 1843 on Broadbalk resulted in a SOC of 0.031 kg kg^{-1} in B-FYM compared to 0.009 kg kg^{-1} on B-PKMg plots receiving only P, K, and Mg with no additional organic additions or mineral N fertilizers inputs (Table 2). In the sandy soil at Woburn, none of the rates of straw addition resulted in a measurable increase in SOC content of the soil. The effect of straw addition on biomass C was not significant ($P = 0.197$). In the following tests, the two extremes of straw incorporation were compared (F0 and F4 in Table 2).

Aggregate Strength, Friability, and Stability

In B-FYM, friability and stability of aggregates were significantly increased compared to B-PKMg, but the additional soil C from FYM addition had no effect on aggregate tensile strength (Table 2). The mean weight diameter of aggregates, from the stability tests, was significantly higher in B-FYM (0.47 mm) compared to B-PKMg (0.37 mm). In the Far Field samples (F0 and F4), with different straw addition treatments, the tensile strength and friability of aggregates did not show any significant treatment differences. Straw application at this site had no significant effect on aggregate stability as indicated by mean weight diameter of aggregates (F0 and F4, Table 2).

Consolidation Characteristics of Different Soil Types

The void ratio of soils with different textures and organic matter contents are plotted against $Log_{10}(\sigma)$ both for normal consolidation and the critical state conditions (Fig. 2 and 3). The steepest slope (Table 3a) is obtained from the B-FYM soil, which has the greatest SOC and clay content and has the highest porosity.

For the B-FYM and B-PKMg soils (Fig. 2), grouped regression showed that the transition from NCL to CSL produced slopes and intercepts that were additive (Table 3a). This means that the increase in both slope and intercept (i.e., transition from Eq. [1] to Eq. [2]) for each soil following deformation from NCL to the CSL is by the same increment. For F0 and F4 soils, relationships between void ratio and $Log_{10}(\sigma)$ are parallel (Fig. 3,
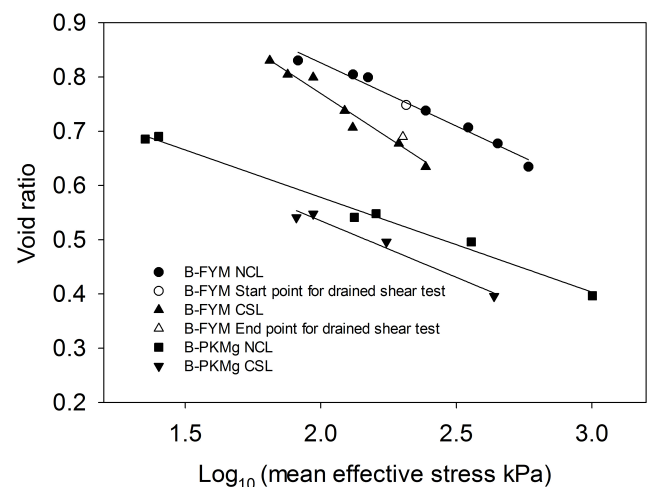

Fig. 2. Normal consolidation (NCL) and critical state (CSL) behavior of soils from the Broadbalk Wheat Experiment (started 1843) at Rothamsted Research, UK; 35 t farmyard manure (FYM) ha^{-1} yr^{-1} in autumn (B-FYM) or inorganic fertilizers P, K, Mg, but no N (B-PKMg). The solid symbols show normal consolidation (circles and squares) followed by shear deformation at a constant porosity to the critical state condition (triangles). The open symbols show the shear deformation of a soil from the normal consolidated condition (circle) to the critical state condition (triangle) at a constant mean effective stress, during a drained test.
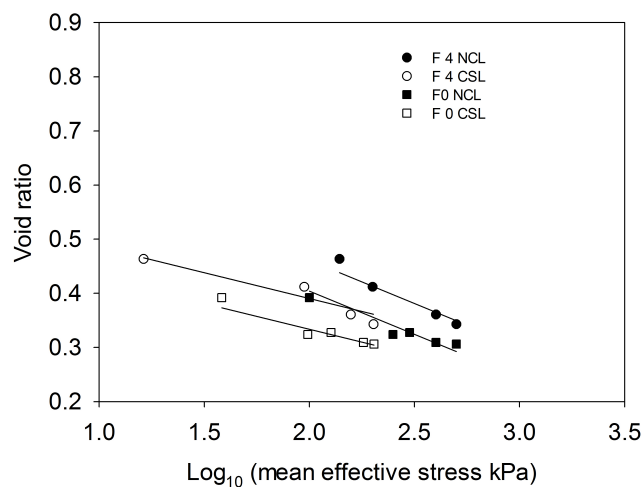
Fig. 3. Normal consolidation (NCL) and critical state (CSL) behavior of soils under "Amounts of Straw" experiment (since 1986) at Far Field, Woburn Experimental Farm, Bedfordshire, UK; Straw baled and removed (No straw) and four times the annual straw production rate (straw chopped and spread before ploughing at about 16 t ha⁻¹).

Table 3b) but different between NCL and CSL. For F0 and F4, the slope of the CSL was smaller than that of the NCL, which was the opposite for both B-FYM and B-PKMg soils where the slope of the CSL was steeper than that of the NCL.

We confirmed that the critical state condition is achieved irrespective of the stress path during deformation (compare the drained and undrained tests in Fig. 2). The drained test took 24 h whereas the undrained test can be completed in a few hours.

DISCUSSION
The Deformation Characteristic

Both soil type and SOC determined the slopes and intercepts of the NCL and CSL (Fig. 2 and 3). With data from this study and the literature (Hettiaratchi et al., 1992; Petersen, 1993; O'Sullivan and Robertson, 1996; Whalley et al., 2012b), a plot of the slope of the CSL against the slope of the NCL shows that they tend to be correlated (Fig. 4). A similar plot was obtained with the intercepts, which along with λ could be used to normalize the compression characteristic as described by Burland (1990). The high correlation makes the measurement

Table 3. Values of the fitted parameters of the consolidation characteristics of soils used in the present study for the normal consolidation lines (NCL) and the critical state lines (CSL). The standard errors are shown in parenthesis. The fitted parameters were determined with grouped regression in Genstat. When different slopes are given, they are statistically different at $P < 0.05$.

(a) Deformation × soil combination	Intercept (N) ± SE	Slope (λ) ± SE
CSL × B-PKMg	0.9899 ± 0.0458	−0.2295 ± 0.0207
CSL × B-FYM	1.3600 ± 0.044	−0.2947 ± 0.0205
NCL × B-PKMg	0.9233 ± 0.0219	−0.1700 ± 0.0099
NCL × B-FYM	1.2934 ± 0.039	−0.2352 ± 0.0167

(b) Deformation × soil combination	Intercept (N) ± SE	Slope (λ) ± SE
CSL × F0†	0.5242 ± 0.0286	−0.0953 ± 0.0138
CSL × F4	0.5810 ± 0.0278	
NCL × F0	0.7231 ± 0.0534	−0.1596 ± 0.0218
NCL × F4	0.7801 ± 0.0535	

† Straw 0 and Straw 4 denotes no straw and an addition of four times annual straw yield.
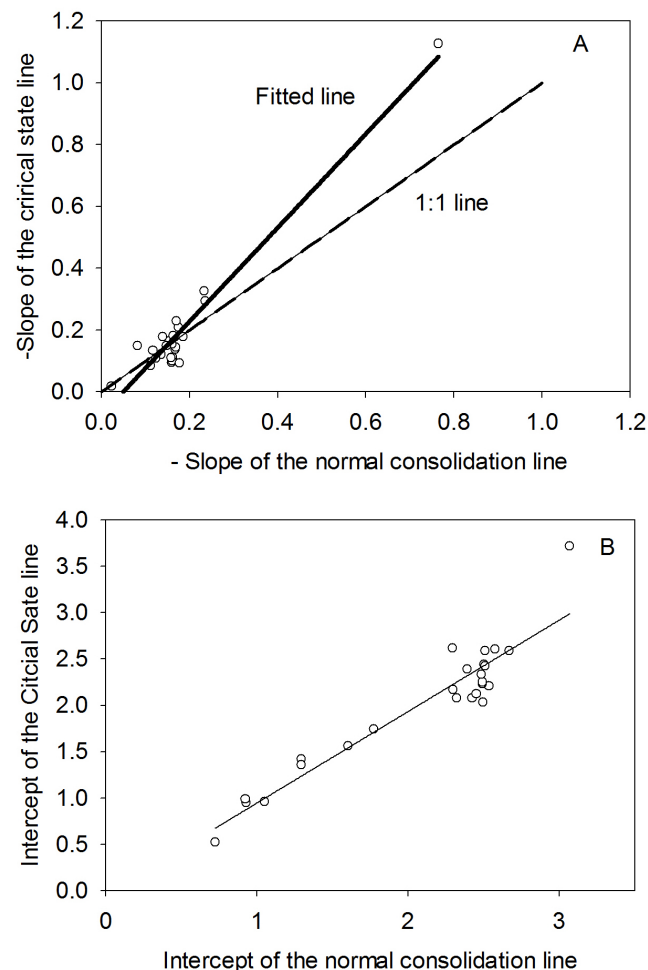

Fig. 4. A plot of the slope of the critical state line (CSL) against the slope of the normal consolidation line (NCL) (a) and the intercept of the CSL against the intercept of the NCL (b).

of both the NCL and CSL unnecessary if the measurements are simply to compare the characteristics of different soils since little added value can be gained with knowledge of both deformation curves. The CSL is a unique relationship for a given soil, which is independent of the stress path, which has been demonstrated for B-FYM (Fig. 2). Thus, this may provide a more robust approach to compare different soils than consolidation curves where their position depends on the ratio of axial to normal stress (Mitchell and Soga, 2005). More commonly, deformation is characterized with the uniaxial compression test (Gregory et al., 2006). In this test, there is an uncontrolled ratio of axial to radial stress, and the deformation path is likely to be in an arbitrary position between the NCL and CSL and, hence, the slope of compression curves measured in this way may not conform to expected soil compression models. Indeed, the anomalous result of the dependence of the slope of the compression characteristic on the initial void ratio has been reported (Keller and Arvidsson, 2007; Arthur et al., 2012, 2013; Keller et al., 2011). Keller et al. (2011) noted that water content–pressure of soil in uniaxial test is not controlled and varies during the test, and this may be an explana-

tion for the slope of the compression characteristic depending on the initial void ratio. Although the uniaxial compression test is quick and intuitively relevant to the field situation, Keller et al. (2011) report that the slope of the compression characteristic is only weakly related to soil characteristics (e.g., clay content and organic matter content). In contrast, the NCL determined under isotropic stress with controlled water pressure provides compression characteristics, which are very sensitive to soil type and organic matter (see the following section). O'Sullivan and Robertson (1996) and Petersen (1993) also report large effect of soil type on its critical state parameters. It seems that because of the uncontrolled stress ratio and in some cases water pressure (making the calculation of effective stress more difficult), the simple models fitted to uniaxial compression data may be inadequate to detect the effect of soil type and management in the compression data.

The compression curves we determined in this work are linear and consistent with those reported for clays by Burland (1990) who used uniaxial compression with controlled water pressure. We also note that in sands a relatively linear NCL up to effective stresses as high as 80 MPa where particle breakage occurs have been reported (Cheng et al., 2005). The sigmoidal curves were obtained with uniaxial testing by Gregory et al. (2006), which are most likely to result from the use of applied rather than effective stress; this cannot be estimated without knowing the pore water pressure.

For most of the soils, the slopes of the NCL and CSL were parallel (or close to parallel, Fig. 4). This means that in underconsolidated soils, the maximum possible densification on shear is independent of the initial soil density. An exception is the high organic matter arable B-FYM treatment (Fig. 2), which had a much steeper CSL than NCL. In this soil, a more compressed underconsolidated soil is capable of greater densification on a shear than a loose soil.

A limitation of our deformation testing is that it was performed on saturated soils. This was because it is quicker since there is no need to allow long periods of time to equilibrate at a matric potential. Volume measurement of saturated soil in triaxial testing is also much easier, although it is still possible to do on unsaturated soil. A significant advantage of testing saturated soils is the effective stress supported by the soil fabric can be calculated with greater certainty and allow greater clarity in the interpretation of the data.

Effect of Soil Organic Carbon on Deformation Characteristics

Although the soil texture has a large effect on the position of the NCL and CSL (Fig. 2 and 3), SOC content has a significant effect as observed by comparing B-FYM with B-PKMg and F0 with F4 (Fig. 2 and 3). The straw incorporation experiment at Far Field had only been running for 26 yr, and the soil had much smaller clay content and, hence, was weakly structured and less well-suited for accumulating organic matter (Johnston et al., 2009). The SOC content of the F4 soil (high annual rate of straw incorporation) was no different from the F0, which had no straw incorporated (Table 2). Even soil microbial biomass C content, regarded as a sensitive indicator of the direction of change in SOC was not significantly greater in F4 compared with F0 (Table 2). Despite this, we still found differences between the NCL and CSL in the two Far Field treatments due to soil management (straw incorporation). The structure of soil is destroyed during critical state deformation to the point where only textural pore space contributes to the soil's behavior (Kirby, 1991). Our data show clearly that regular inputs of straw can alter the position of the CSL on Far Field soil (compare F0 to F4 in Fig. 3). The CSL for F4 was in the same position as the NCL for F0.

The Far Field (F0 and F4) data suggest that the measurement of deformation characteristics is an extremely sensitive measure of the effects of soil management on soil physical characteristics. We have identified a measurement that can be used to quantify changes in the structure of repacked soil before any detectable increase in total SOC or even microbial biomass C content is evident. Our findings support the anecdotal accounts of farmers in England who have incorporated straw and reported an improvement in the soil physical condition, while at the same time increases in total SOC have not been detected.

The position of the CSL on the porosity-effective stress plane may provide a valuable reference datum to monitor changes in soil physical condition. While the determination of the CSL is more complex than most soil measurements, in sandy soils there is a rapid procedure (Santamarina and Cho, 2001). The critical state parameters may also be determined more rapidly from shear box testing than triaxial tests (Kirby, 1998).

Effect of Soil Organic Carbon on Aggregate Strength and Stability

At the aggregate scale, we found no effect of SOC on aggregate strength, friability, or stability in Far Field soils (F0 and F4). Large difference in organic and biomass C between B-FYM and B-PKMg treatments resulted in an increase in friability and stability, but they had no effect on the tensile strength of aggregates. Much larger and significant differences in aggregate stability, tensile strength, and friability at the aggregate scale are reported by Watts and Dexter (1997, 1998) on Rothamsted soils similar to Broadbalk, when comparing uncultivated, grassland, and uncropped fallow soils with arable soils. Changes in aggregate stability have been observed long before changes in total SOC are detectable (Baldock et al., 1987). These changes have been attributed to changes in the amounts of fine roots and fungal hyphae, which strengthen failure zones through physical entanglement and which also act as sources of C for bacteria, therefore, contributing to increases in cementing materials (Tisdall and Oades, 1982). These stabilizing materials are likely to represent a tiny part of total C content. However, our work shows these tests to be insensitive to more subtle changes associated with large differences in the rate of straw incorporation.

It is possible that the effect of the treatments is up scaled according to the number of particle-to-particle bonds participat-

ing in the particular mode of failure. This effect will be orders of magnitude higher in a core where the complete volume is under deformation compared to an "area" in the tensile fracture of an aggregate. Our data suggests that the sensitivity of different physical tests of soil to the effects of SOC (or biomass C) is as follows: deformation > stability > friability > tensile strength (tensile strength is least sensitive). Unfortunately, deformation tests are rarely used in comparisons of soil physical characteristics. Instead, stability tests, which can be performed more quickly with no specialist equipment, are widely used. Although the uniaxial test is simpler to perform than the triaxial test, we note that interpretation of results in terms of soil properties (e.g., clay content or SOC) seems uncertain (Keller et al., 2011).

Implications for the Behavior of the Soil in the Field

Tensile tests and the associated friability are used empirically to determine which soils will respond more positively to cultivation and to identify optimum water contents for seedbed preparation. Similarly, stability tests indicate the ability of different soils to resist crusting and erosion. These tests tend to be used as indices; neither has provided a mechanistic understanding of soil behavior, which can be up scaled in numerical models. In contrast, data from triaxial tests can be used to make predictions of soil behavior, for example in the prediction of penetrometer resistance (Farrell and Greacen, 1966).This predictive capacity that results from triaxial testing is a clear advantage over other tests of soil physical behavior, although there are issues that need to be overcome. The deformation of soil is very sensitive to soil water status, which is reflected in triaxial tests on unsaturated soil (e.g., Alonso et al., 2010; Adams and Wulfsohn, 1997). Wulfsohn et al. (1998) have shown that matric potential will stay approximately constant only when the degree of saturation is low or when the applied stress is low. Otherwise large changes in matric potential can occur during deformation, which need to be monitored. The repeated loading of soil can alter the relationships between porosity and deformation (O'Sullivan and Robertson, 1996), which needs to be taken into account when applying the results from triaxial testing to the field environment.

CONCLUSIONS

We have shown that soil organic C content has an important effect on the deformation characteristics of soil. Deformation characteristics, determined with triaxial testing were more sensitive to small changes in soil management, designed to increase soil organic C content, than measurements of aggregate tensile strength, friability, or stability. Deformation characteristics of a sandy loam soil showed effects of straw incorporation when no significant difference in SOC content or microbial biomass C could be detected. Microbial biomass is regarded as a particularly sensitive indicator and predictor of changing SOC content (Powlson et al., 1987). The even greater sensitivity of triaxial testing to measure deformation characteristics response to management practices designed to alter SOC is a major new finding. Even though the method of measurement currently requires a relatively complex procedure, we suggest that this new finding indicates that the approach should be pursued further in an attempt to develop sensitive tests for soil physical characteristics that are sufficiently simple to be of practical value, but are based on a rigorous understanding of basic soil physical properties.

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