Soil Use and Management

Soil Use and Management, September 2009, **25,** 284–292 doi: 10.1111/j.1475-2743.2009.00223.x

Aggregate stability in organically and conventionally farmed soils

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Abstract

A range of factors that influence aggregate stability and soil erodibility were analysed for soils sampled from land managed under contrasting agricultural methods. These included: an organic farm; a conventional farm that incorporated organic fertilizers; a conventional farm that only used inorganic fertilizers; and a non-cultivated control site. The stability of aggregates that compose the bulk soil structure (macroaggregates), and aggregates that were mobilized from the soil by simulated rainfall and surface runoff (microaggregates), were evaluated in terms of the soil fragmentation fractal dimension, organic carbon content and ATP (adenosine 5′-triphosphate; a signature of live biomass) concentration. The results were used to interpret the existing physical condition of the soils, the (microbial) processes that contribute to that physical structure, and how both pedogenic processes and existing soil quality are influenced by agricultural methods. The soils sampled for this study were demonstrated to be multi-fractal in nature: soils with greater bulk density were composed of more stable macro-aggregates, which, in turn, fragmented into larger, more stable micro-aggregates, rendering the entire soil structure less erodible. Soil erodibility and sustainable soil management should therefore be approached at multiple scales. The primary control on both macro- and micro-aggregate stability was determined to be the organic matter input to the soil, as represented by measurements of organic carbon and ATP. Organic content was greatest for the non-cultivated soil, which reflects the degradation of organic reserves in cultivated soils. For cultivated soils, it was not possible to differentiate aggregate stability for soils managed under organic or conventional (i.e. using biological and inorganic fertilizers) farming practices, but aggregates of soils that only received artificial fertilizers consistently exhibited less stability.

Keywords: Aggregate stability, erodibility, fragmentation fractal dimension, micro-aggregate, macro-aggregate, organic agriculture

Introduction

Soil aggregate structure and aggregate stability are important factors that contribute to sustainable soil quality and soil erosion potential (Barthès & Roose, 2002; Shepherd *et al.*, 2002; Bronick & Lal, 2005). It follows that the physical properties of aggregates have a significant influence in linking catchment surfaces to the stream channels in terms of the susceptibility for aggregate fragmentation and fine sediment mobilization by rainfall and surface runoff (Mbagwu & Bazzoffi, 1998; Barthès & Roose, 2002). This has implications for the delivery of fine sediment and associated nutrients and contaminants from catchment surfaces to water courses, and the physical degradation of channel habitats.

With respect to soil erosion and transfer potential, soil composite particles can be classified as macroaggregates and microaggregates. Macroaggregates are defined in this study as aggregates that constitute the bulk soil structure, and which are essentially sedentary, but could be mobilized by processes such as mass movement. Microaggregates are defined here as aggregates of a size that can be mobilized by hydraulic processes, and which constitute part of the sediment load that is transferred by runoff and throughflow processes across the catchment. In this context, there is no

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Received January 2009; accepted after revision May 2009

constant particle size threshold to distinguish the two aggregate types, as particle mobility would be determined by the nature of the rainfall – runoff/throughflow processes. Macroaggregates may be fragmented to a size small enough to allow mobilization, e.g. by raindrop impact, and, in contrast, microaggregates may be consolidated into larger, relatively immobile composite particles by pedogenic processes.

Both soil micro- and macro-aggregate structure are intrinsically linked, as summarized in the aggregate hierarchy concept developed by Tisdall & Oades (1982) and Oades (1984). It is generally accepted that organic matter is a primary control on aggregate formation, which, in turn, relates to organic matter stabilization and long-term bulk soil stability. It is also recognized that microbial activity (relating to the decomposition of organic matter) is an important process in micro-aggregate formation and, in particular, the early stages of aggregate formation following organic matter input to soil (Tisdall & Oades, 1982; Cosentino *et al*., 2006). The principal mechanism of microbially-induced aggregation relates to the active binding properties of microbial polymeric exudates. It follows that investigations of aggregate structure should incorporate analysis of the living and active microbial associations existing within soil. Living microbial biomass can be quantified by the analysis of adenosine 5′-triphosphate (ATP), using bioluminescence techniques (Lundin *et al*., 1986; Karl, 1993). These techniques have been successfully applied to the analysis of the microbial content of soils, e.g. Han *et al*. (2007), but rarely has the technique been directly applied to understanding aggregation processes.

Soil organic matter is preferentially contained in microaggregates, and it follows that sediment erosion and nutrient loss from soils depend primarily upon fragmentation of macroaggregates and the mobilization of microaggregates (Mbagwu & Bazzoffi, 1998; Six *et al*., 2004; Green *et al*., 2005; Kuhn, 2007). Aggregate stability is therefore a good indicator of general soil quality, and an important property for soil sustainability. It is known that cultivated soils tend to have decreased aggregate stability (Barthès & Roose, 2002; Green *et al*., 2005).

The soil aggregate size distribution is a consequence of soil structure. The physical analysis of aggregates therefore represents a technique for expressing soil structure quantitatively. Researchers have, for decades, attempted to characterize aggregate and bulk soil structure using a single parameter. Increasing attention has been given to advances in fractal theory, and a scaling parameter, the fractal dimension, has been used by many authors to characterize the soil aggregate size distribution (e.g. Martínez-Mena *et al*., 1999). The value of the fractal dimension D is equal to the absolute value of the exponent in the relation $N_{>x} = k(x)^{-D}$, where $N_{>x}$ is the cumulative number of objects greater than x, and k is a constant equal to $N_{>x}$ at $x = 1$. Lower values of D are associated with soils dominated by larger aggregates (Martínez-Mena *et al*., 1999). In terms of sustainable soil quality and erodibility, a lower value of D could be considered beneficial, and would be associated with greater soil aggregate stability and greater soil bulk density.

Land cover and land management practices, particularly cultivation methods, can significantly influence soil properties. This has had a significant bearing on the increasing shift from conventional to organic farming in recent years, although, in terms of the physical and nutrient composition of soils, it remains unclear if organic agriculture is beneficial for soil sustainability. It is accepted that soil quality and fertility are dependent upon organic matter content (e.g. Albiach *et al*., 2001; Melero *et al*., 2006), but evidence is cited for (e.g. Siegrist *et al*., 1998; Schjønning *et al*., 2002; Shepherd *et al*., 2002; Bioa *et al*., 2003; Melero *et al*., 2006) and against (e.g. Greenland, 2000; Løes & Øgaard, 2001; Shepherd *et al*., 2002; Gosling & Shepherd, 2005) the increased agronomic sustainability of organic versus conventional farming methods.

Existing studies suggest that macroaggregate stability is significantly higher in organically farmed soils (Siegrist *et al*., 1998; Shepherd *et al*., 2002), although evidence remains scarce. Little attention has been directed toward the influence of organic or conventional agriculture on the stability of microaggregates. The aim of this study was to compare the effects of organic and conventional agriculture on both soil micro- and macro-aggregate stability. This represents a research need for evaluating the impacts of land management practices on the sustainable quality of soils and associated water courses.

Methods and materials

Overview and sample collection

Soil samples were collected from four contrasting sites on farm land within a small area in southern Devon, England. Brief descriptions of each site are presented in Table 1. Soils at all the sample sites were known to be typical brown earths of the Denbigh 1 association (eutric cambisol by the Food and Agriculture Organization classification system), which is characterized as being well-drained fine loamy and fine silty soil over rock (Soil Survey of England and Wales, 1983). The sites were selected so that samples represented three contrasting agricultural methods and a non-cultivated control. Underlying geology, soil type, slope angles and climate conditions were consistent for all the sampling locations. In all cases, land had been managed by the same respective methods for at least 10 years.

The samples were analysed for a suite of physical properties, and also for content of carbon and ATP. Physical analysis of the soil samples incorporated measurements of soil texture, bulk soil fragmentation, the size and stability of aggregates mobilized from samples by simulated surface

Table 1 Soil sample site abbreviations and agricultural methods

Site/ abbreviation	Definition	Agricultural conditions and recent tillage history
C_{AR}	Conventional – Inorganic	Conventional agriculture, inorganic fertilizers only. Tilled < 1 month prior to sampling
C_{BIO}	Conventional – Biological	Conventional agriculture, inorganic and biological (cattle manure and slurry) fertilizers. Tilled < 6 months prior to sampling
ORG	Organic	Organic agriculture, cattle manure as fertilizer. Tilled < 1 month prior to sampling
NC	Non-cultivated	Control site, set aside from cultivation under the Countryside Alliance scheme. Never tilled

runoff (microaggregates), and the size and stability of aggregates that composed non-mobilized samples (macroaggregates).

All samples were collected on the same date from the soil surface (top 5 cm), in triplicate, and as blocks in $30 \times 40 \times 5$ cm trays, with minimal disturbance to the soil block. Three groups of triplicates were collected at each site, with each group spaced 10 m apart in the field. Samples collected for the analysis of microaggregates were stored in a greenhouse prior to analysis. Microaggregate analysis was conducted within 4 days of sampling, with samples analysed in an order that meant the average storage time for samples from each land use was the same. Soil moisture content in these samples did not vary significantly from field conditions to the time of microaggregate analysis. Samples for bulk fragmentation and macroaggregate analysis, which were air-dried prior to analysis, were collected separately from samples collected for microaggregate analysis, but in the same manner, and from adjacent locations in the field.

Fragmentation fractal dimensions and macroaggregate characteristics

Air-dried samples were sieved for 30 s on nested sieves with apertures of 16, 8, 5.6, 4, 2, 1, 0.5 and 0.25 mm. The contents of each sieve were measured for aggregate mass and volume, and bulk densities were calculated from these results. Fragmentation fractal dimensions were calculated for each sample, using the logarithmic scaling relationship

$$N_{>x} = k(x)^{-D}, \tag{1}$$

where $N_{>x}$ is the cumulative number of aggregates greater than size x, k is a constant equivalent to $N_{>x}$ at $x = 1$, and the value of D is equal to the fragmentation fractal dimension (D_f). Values of N were derived from measurements of aggregate mass and volume distributions for aggregates in the size range $0.25 < d < 16$ mm, based on the method of Martínez-Mena *et al.* (1999), which assumes constant aggregate shape. A quantity proportional to the number of aggregates in each size class, $N(d_i)$, was calculated as:

$$N(d_i) = M(d_i)/{d_i}^3\rho_i, \tag{2}$$

where $M(d_i)$, d_i and ρ_i are the mass, mean diameter and density of aggregates respectively, in the ith size class. The constant k was derived from

$$N(d_k) = \sum N(d_i), \tag{3}$$

where d_k is the mean diameter of the kth (largest) size class. D_f is equal to the slope of the linear regression between $N(d_{ik})$ and $N(d_{ik})/N(d_k)$.

Macroaggregate stability was measured for air-dried aggregates retained on sieve apertures of 8, 5.6, 4 and 2 mm diameter using a rainfall simulator, extending the method of Martínez-Mena *et al.* (1999), who analysed aggregates of uniform size. The use of rainfall simulation has been demonstrated to be a useful analytical tool for soil stability studies (e.g. Martínez-Mena *et al.*, 1999; Pachepsky *et al.*, 2009). Twenty-five particles of each size class were counted onto a graded-aperture mesh, and subjected to simulated rainfall at an intensity of 50 mm/h from a height of 186 cm and with a mean raindrop diameter of 460 μm. If, at the end of the rainfall simulation, the soil particles were composed of non-aggregated particles larger than the relevant mesh aperture, the experiment was repeated, to give results for 25 aggregates for each size class per sample. The rainfall simulator had a rotating base (at a speed of 2 rpm) to ensure even distribution of raindrop impact. Simulated rainfall was in bursts of 30 s for a cumulative duration of 20 min, with the number of aggregates surviving raindrop impact counted at each interval.

Microaggregate characteristics

Microaggregates were mobilized in simulated soil runoff from block soil samples, which were subjected to simulated rainfall of the same intensity and fall height as described above, but with the samples in fixed position at a 5° angle. Runoff containing fine sediment was collected in 500 mL polyethylene bottles, and promptly analysed for microaggregate particle size, using a LISST-100 laser diffraction particle sizer, following dilution to a concentration that could be measured by using the LISST-100. The stability of microaggregates in the runoff sediment was then analysed by measuring the transition of particle size distributions resulting from controlled ultrasonic transduction (Mentler *et al.*, 2004). Runoff sediment from a sample was collected into a centrifuge tube (total volume 60 mL) and was destabilized by clamping the centrifuge tube 90% submerged in the centre of a 975 mL Malvern MSX 17 ultrasonic bath, which had a variable 0–50 Watts input and a nominal frequency of 40 kHz. Ultrasonication was applied sequentially, in bursts of 120 s at 50%, 75%, and 100% power.

Pilot tests showed that total sample dispersal would be achieved by the final step, which equated to a cumulative disruptive force of 20 J/mL. Dispersal was validated by there being no subsequent changes in the size distribution following further ultrasonication, and also by observation of sub-samples under a microscope. Particle size was analysed after each treatment stage. The degree of fine sediment aggregation at each step was calculated as the percentage increase from the median absolute particle size (i.e. the particle size of completely dispersed samples) to the median particle sizes measured previously.

Soil texture

Inorganic soil texture was measured using a Malvern Mastersizer laser diffraction particle sizer, following removal of organic matter by H_2O_2. A Mastersizer was used for measurements for soil texture because the LISST-100 has a lower size threshold of 2.5 μm, and is thus unsuitable for the analysis of clays. However, the arrangement of optics and the open sample analysis zone of the LISST-100 was considered better suited for the analysis of effective particle size analysis. There were no direct comparisons of data yielded from the different measurement systems, and, as such, there were no concerns relating to the interpretation of data in terms of potential operationally-defined errors.

Organic and biological analysis

Total and organic carbon was measured for sub-samples of air-dried soil using a Skalar Primacs SLC TOC analyser which employs high temperature catalytic oxidation with NDIR detection in a pure oxygen atmosphere. Adenosine Triphosphate was analysed using luminescence techniques (Lundin *et al*., 1986) following the methods described in a commercially available reagent kit (ATP Biomass Kit HS; BioThema AB, Sweden) and using an EG&G Wallax Trilux Liquid Scintillation and Luminescence counter. Measurements for carbon and ATP were taken from triplicate sub-samples that had been frozen at the time of sample physical analysis. It should be noted that neither carbon nor ATP values that are reported below are suggested to represent *in situ* soil conditions. However, the results for different samples are considered comparable.

Results and discussion

Brief descriptions of each sampling site are provided in Table 1 with definitions of the adopted abbreviations for each agricultural condition. Soil type was known to be consistent between the sample sites. Measurements of the inorganic soil texture of samples collected for this study confirmed that texture did not vary between the sites. On this basis it was assumed that any differences in soil properties that were detected between the sites could be attributed to agricultural practices. Differences between soils are quantified using the relationships between particle stability and other soil properties, and expressed as rank scores of soil properties, where higher scores were given to properties that are considered to represent lower erodibility and greater sustainable soil quality.

Organic soil composition

A summary of the total organic content (% organic carbon) and active biological content (ATP) of the soils is presented in Table 2. Measurements showed that none of the soils contained significant amounts of inorganic carbon. All of the soils were significantly different in terms of organic carbon composition (Mann–Whitney test, P 0.05, n 9 for each soil), but only C_{AR} and NC had significantly different ATP concentrations (Mann–Whitney test, P 0.05). Organic carbon and ATP were not significantly correlated (product-moment correlation, P 0.05). The standard errors for organic carbon data are small in comparison to the mean values, but the spread of data for the ATP results was much wider. This is due to the molecular nature of ATP analysis, which contrasts with the bulk oxidation technique used for measuring organic carbon. While the measurement of biological activity is, in principle, more representative of aggregation processes in soil, the analysis of bulk organic carbon is more applicable to other measurements taken for this study, as the main focus is on bulk soil erodibility. As such, tests for significant relationships between organic and physical variables that are described below focus on measurements of organic carbon content. Soils were ranked according to organic carbon and ATP content in the orders, respectively, $NC > ORG > C_{BIO} > C_{AR}$ and $NC > C_{BIO} > ORG > C_{AR}$. The differences between soil types presented in this study corroborate existing studies (e.g. Melero *et al*., 2006), which have demonstrated that organic reserves mined during cultivation can be replaced more effectively by direct application of organic fertilizers such as manure, rather than artificial fertilizers.

Physical soil composition

The mass distributions of macroaggregates in cultivated soils are bi-modal (Figure 1) with peaks at 2-4 and 8-16 mm. This

Table 2 Mean values (and standard error in parentheses) for organic carbon and ATP content of soil under each land use

Soil	% Organic C	ATP (nM/mg)
C_{AR}	1.89 (0.02)	0.12 (0.02)
C_{BIO}	3.97 (0.08)	0.19 (0.02)
ORG	4.80 (0.04)	0.16 (0.02)
NC	5.47 (0.40)	0.20 (0.01)

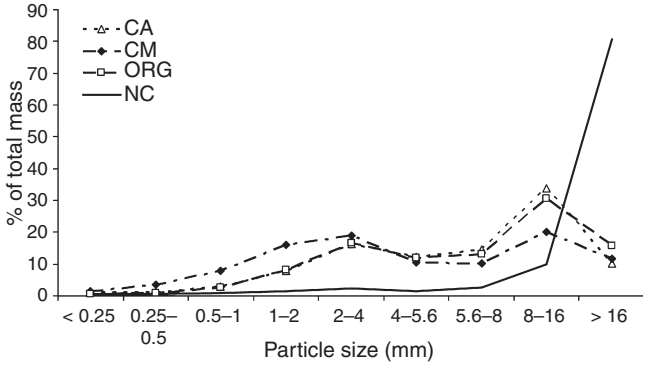

Figure 1 Macro-aggregate size distributions by mass.

contrasts with the non-cultivated control soil which exhibits a strong negative skew. Comparative tests of the respective mass distributions (modified Kolmogorov–Smirnov test [Goldman & Lewis, 1984]; $P = 0.05$) showed significant differences between all sets of soils except for C_{AR} and ORG which were not significantly different.

Soil bulk density distributions are presented in Figure 2, using only those size classes where the upper and lower size boundaries were measured. Bulk densities of particles 0.25–1 mm in size are similar for all soils. Bulk density values peaked in the 2-4 mm size class for C_{AR} soil, and in the 4-5.6 mm size class for C_{BIO} and ORG soils. The peaks in bulk density distributions are attributed to the presence of non-aggregated particles in these size fractions. Mean bulk density values were calculated by weighting the bulk density distribution to the mass size distribution. Weighted mean bulk density values were ranked in the order of NC (1.58 g cm^{-3}) > C_{AR} (1.26 g cm^{-3}) > ORG (1.22 g cm^{-3}) > C_{BIO} (1.18 g cm^{-3}), where a greater mean bulk density is assumed to relate to a lower erosive potential. There is no significant correlation (product-moment coefficient, P 0.05) between mean bulk density and organic carbon content. For the NC soil, bulk density values are similar to the cultivated soils except in the largest size class. This is attributed to the effects of tillage breaking up the macroaggregates in the cultivated samples while macroaggregates become more consolidated over time in the non-cultivated soil.

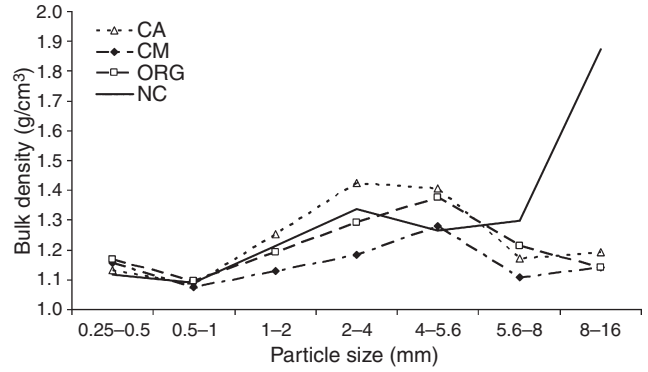

Figure 2 Bulk density distributions.

Macroaggregate size distributions were also characterized using the fragmentation fractal dimension. Regression data for D_f are presented in Table 3, where D_f is the negative slope of the relationship. The soils were ranked according to the mean D_f value for each sample population, in the order NC > C_{AR} > ORG > C_{BIO}. Comparison of D_f values showed that the only significant differences (Mann–Whitney test, $P = 0.1$) were between C_{AR} and C_{BIO}, and C_{BIO} and ORG. A P-value of 0.1 was used because the analytical technique is destructive, and restricted the sample population for each soil to $n = 3$. There were no significant relationships between D_f and organic carbon or ATP content, or with the relative time elapsed since the soils were tilled (c.f. Table 1). The ranking of D_f is the same as the ranking of bulk density, and these two variables are significantly correlated (product-moment correlation −0.67, $P = 0.05$). Soils with lower values of D_f have previously been demonstrated to be more stable, and less susceptible to erosion (Martínez-Mena *et al.*, 1999).

Macroaggregate stability

Macroaggregate stability was assessed directly by measuring the fragmentation of macroaggregates during simulated rainfall. There were no significant relationships between macroaggregate stability and simulated rainfall duration, so overall stability was assessed according to the proportion of aggregates surviving after 20 min of simulated rainfall (Figure 3). In all soils, larger macroaggregates were generally more stable. Macroaggregates of C_{AR} soil were significantly less stable than all other soils in all size classes (Mann–Whitney; $P = 0.1$, $n = 3$ for each soil). The stability of macroaggregates 4–16 mm in size was virtually identical for C_{BIO}, ORG and NC soils. Mean macroaggregate stability was calculated by weighting the stability results to the mass size distribution. Weighted mean percentages of stable aggregates for each soil were ranked NC (86.4%) > ORG (85.6%) > C_{BIO} (71.4%) > C_{AR} (45.7%). Statistical comparisons (Mann–Whitney; $P = 0.1$, $n = 3$ for each soil) showed that macroaggregates of C_{AR} soil were significantly less stable than macroaggregates of all other soils, and there were no other significant differences. The ranking of macroaggregate

Table 3 Regression information for the mean fragmentation fractal dimension (D_f; the negative slope of the relationship) of each soil

Soil	D_f	Intercept	R^2	SE
C_{AR}	2.160	1.963	0.986	0.016
C_{BIO}	2.666	1.714	0.984	0.022
ORG	2.313	1.088	0.985	0.018
NC	2.121	1.976	0.978	0.007

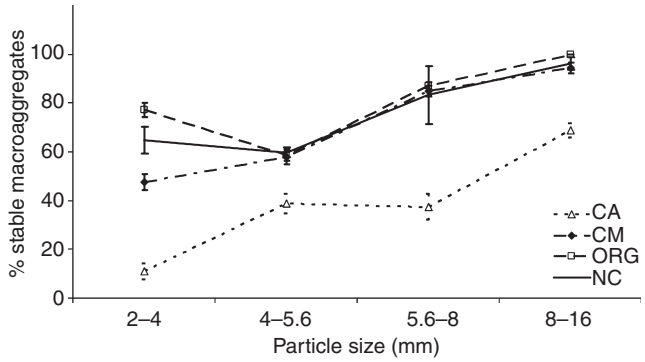

Figure 3 Mean macro-aggregate stability (with standard errors) under simulated rainfall for each soil.

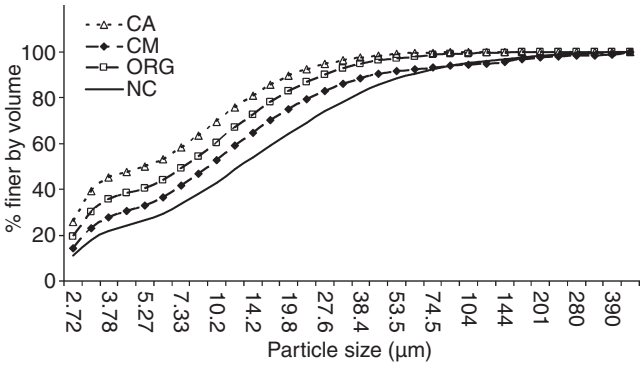

Figure 4 Mean particle size distributions for micro-aggregates in simulated surface runoff from each soil.

stability matched the ranking of organic carbon content, and there was a significant correlation between these properties (product-moment correlation of 0.74, $P = 0.01$). The correlation between macroaggregate stability and ATP concentration was not significant, although the general directional trend was the same as for macroaggregate stability and organic carbon. This is assumed to relate to the molecular nature of ATP analysis (see above), although it does indicate that ATP does have a role in macroaggregate stability. Correlations between macroaggregate stability and mean bulk density, and macroaggregate stability and D_f were not significant. On this basis, organic carbon content, as influenced by agricultural methods, appears to offer a satisfactory explanation for the macroaggregate stability results.

Because of the strength of the correlation between macroaggregate stability and organic content, the variables were analysed using least-squares regression, yielding the predictive equation $St_{MAC} = 9.81C + 29.2$, where $P = 0.04$, $R^2 = 0.55$, and $n = 12$. The low R^2 value was attributable to the leverage of one observation having a large standardized residual, so the regression was re-run without this observation, yielding the relationship $St_{MAC} = 11.1C + 27.5$, where $P = 0.01$, $R^2 = 0.77$, and $n = 11$. These results further demonstrate the importance of organic carbon to sustainable soil quality and erodibility.

Microaggregate stability

Microaggregate size distributions are presented in Figure 4. It should be noted that the mobilized fine sediment contained a portion of non-aggregated particles, but it was not possible to assess the relative contributions of microaggregates and non-aggregated grains to the total load using the LISST-100 sizing technique. Fine sediment in the simulated surface runoff samples is referred to in terms of microaggregates for simplicity but it represents all breakdown products of macroaggregates. Microaggregate size distributions were compared using a modified Kolmogorov–Smirnov test ($P = 0.05$), and it was determined that C_{AR} soil was significantly different from C_{BIO} and NC soils, and NC was significantly different from C_{AR} and ORG soils. The soils were ranked according to microaggregate d_{50}, in the order NC (11.61 μm) > C_{BIO} (8.86 μm) > ORG (6.99 μm) > C_{AR} (4.81 μm). Microaggregate d_{50} correlates significantly with macroaggregate stability (product-moment correlation of 0.72, $P = 0.05$), and with organic carbon content (0.60, $P = 0.05$), but does not correlate with D_f or mean bulk density. The significant relationships show that more stable soil bulk properties will tend to yield larger microaggregates. Larger microaggregates could also be considered less susceptible to transfer by surface runoff, although this would depend on their structural stability.

Microaggregate stability was assessed by destabilizing the samples using ultrasonic transduction. To compare microaggregate stability between soils, least-squares regression relationships between microaggregate size and cumulative destabilizing force were used to analyse relative microaggregate stability, i.e. the relative ease with which microaggregates could be progressively fragmented. The results are presented in Table 4. The regression calculations did not include data for the final destabilization stage (20 J/mL), the level at which total aggregate dispersal was achieved, because this would have effectively standardized the results. It was determined from the slopes of the regression relationships that soil microaggregate stability could be ranked in the order C_{BIO} > NC > C_{AR} > ORG. The regression slope values for microaggregate stability correlate significantly with values for D_f (−0.71; product-moment correlation,

Table 4 Regression information for the relationships between microaggregate stability (St_{MIC}) and applied disruptive force (J) for each soil

Soil	Equation	R^2	P
C_{AR}	$St_{MIC} = 6.10J + 17.3$	0.82	0.10
C_{BIO}	$St_{MIC} = 4.28J + 9.97$	0.89	0.06
ORG	$St_{MIC} = 6.75J + 7.76$	0.95	0.02
NC	$St_{MIC} = 4.51J + 19.9$	0.69	0.17

$P = 0.05$), but do not correlate with any other variable. The relationship between the susceptibility of microaggregates to fragment and the D_f of bulk soil emphasises the multi-fractal structure of soils. Soils are composed of aggregates, which themselves are composed of aggregated sub-units, which are ultimately composed of primary matter (mineral, non-living organic and living biological components). The absence of other relationships between microaggregate stability and bulk soil properties is logical, in that microaggregates that can be mobilized from the bulk soil profile by raindrop impact and surface runoff would be expected to behave in a disparate manner to stable and sedentary macroaggregates.

The results of the progressive destabilization of micro-aggregates are presented in Figure 5. The results indicate that a large proportion (represented by a 57% decrease in d_{50}) of microaggregates in NC soil can be destabilized with a disruptive force (3.1 J/mL) but microaggregates that survive this treatment are more stable than the equivalent particles in other soils (as represented by the subsequent decreases in the rate of destabilization). Microaggregates of C_{BIO} soils exhibit a similar trend, albeit to a lesser extent. This relates to the nature of microaggregation processes. Aggregation is primarily dependent on the activity of microbial organisms that decompose organic matter within the first few weeks following the addition of organic matter to the soil (Tisdall & Oades, 1982; Cosentino *et al.*, 2006). The type of organic matter in the soil becomes unimportant over a period of 3–6 months (Calbrix *et al.*, 2007), although the total organic content remains crucial in the long-term. The NC, C_{BIO} and ORG soils are known to have the greatest concentrations of ATP (Table 2) reflecting higher active biological activity, but tillage in ORG and C_{AR} occurred relatively recently (1 month) compared to C_{BIO} (6 months) and NC (never). The results presented in Figure 5 suggest that significant proportions of 'new' microaggregates, formed by microbial activity, were not yet fully structurally stable, and fragmented when exposed to low energy, whereas more 'mature' microaggregates that were able to develop in NC and C_{BIO} were much more stable. In contrast, microaggregates of ORG and C_{AR} soils were least stable over the range of ultrasonication, which may reflect a lack of older more stable microaggregates.

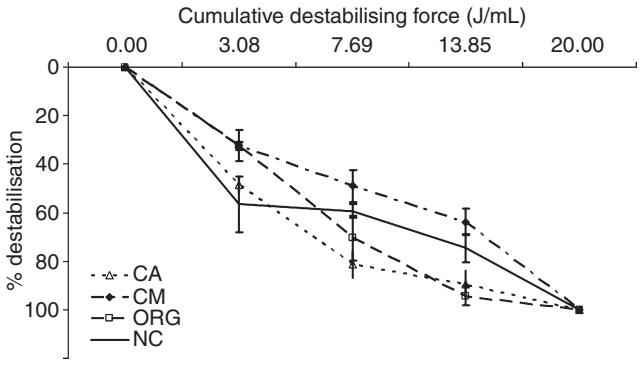

Figure 5 Mean destabilization (with standard errors) of micro-aggregates for each soil.

Summary of results

A summary of the rank order of a range of soil properties with respect to soil cultivation is presented in Table 5. A ranking of one indicates a beneficial soil quality, i.e. sustainable quality for soil that is likely to have low erodibility. Given the number of soils in the study, statistical analysis of the rank orders was not considered appropriate. It is apparent, though, that NC soils exhibit the highest aggregate stability and highest general soil quality, as would be expected. However, the relative effects of agriculture, when comparing organic farming, conventional methods incorporating organic fertilizers, and conventional methods using inorganic fertilizers only, are less clear. In broad terms, ORG soil tends to exhibit higher aggregate stability and higher general soil quality, and C_{AR} soil tends to exhibit lower aggregate stability and lower general soil quality. It is difficult to elucidate the stability of C_{BIO} and ORG soils, despite the contrasting agricultural methods.

Conclusions

Aggregate stability, and a range of factors that potentially contribute to stability, were analysed for soils sampled from land managed under contrasting agricultural methods; namely an organic farm, a conventional farm that incorporated organic fertilizers, a conventional farm that only used artificial fertilizers, and a non-cultivated control site. It is

Table 5 Summary of soil property rankings for each soil

Rank order	Macro-aggregate stability	Micro-aggregate stability	% organic C	ATP content	Mean bulk density	D_f	Micro-aggregate D_{50}
1	NC	C_{BIO}	NC	NC	NC	NC	NC
2	ORG	NC	ORG	C_{BIO}	C_{AR}	C_{AR}	C_{BIO}
3	C_{BIO}	C_{AR}	C_{BIO}	ORG	ORG	ORG	ORG
4	C_{AR}	ORG	C_{AR}	C_{AR}	C_{BIO}	C_{BIO}	C_{AR}

apparent that numerous factors contribute to soil aggregate stability, including agricultural methods. It is demonstrated that a multiple analytical approach is beneficial for elucidating the complex inter-relationships between soil properties. Because soil structure is multi-fractal in nature, multiple-scale analyses should be used to interpret soil processes. The analysis of ATP in addition to total organic carbon was a useful tool for interpretation of the underlying processes that contribute to bulk soil properties. Organic matter content (both organic carbon and living and active biological material, as represented by analysis of ATP) was determined to be the primary control on aggregate stability. In this study, the non-cultivated soils exhibited the greatest aggregate stability, which relates to the absence of mining of soil organic reserves by cropping. Aggregate stability was greater in the soils which had been fertilized using organic matter than the soils cultivated using inorganic fertilizers only. It was not possible to differentiate aggregate stability between soils sampled from the organic farm and the conventional farm that used organic matter as fertilizers. This leads to the conclusion that the addition of organic matter to farmed soils is more important to aggregate stability than the type of farming system. This has important consequences for soil erodibility and sustainable soil quality.

Acknowledgements

The authors gratefully acknowledge the support of the land owners who permitted access for field sampling. Thanks are also extended to Richard Hartley, John Moody and Kevin Solman (University of Plymouth) for their assistance with rainfall simulation and soil texture analysis, ATP analysis, and carbon analysis, respectively. The study was funded by the Seale Hayne Education Trust, and undertaken while the authors were employed at the School of Geography, University of Plymouth (UK).

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