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## Ab ac

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.

**K d** : Aggregate stability, erodibility, fragmentation fractal dimension, micro-aggregate, macro-aggregate, organic agriculture

## I d c

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.

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

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-

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<sub>2</sub>O<sub>2</sub>. A Mastersizer was used for measurements for soil texture because the LISST-100 has a lower size threshold of 2.5  $\mu$ m, 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.

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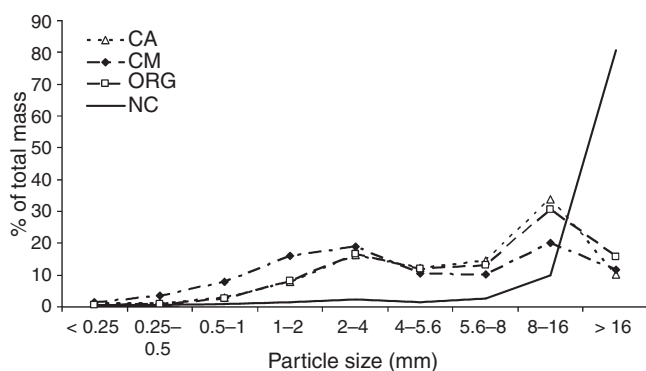


Fig. 1 Macro-aggregate size distributions by mass.

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 ( $1.58 \text{ g cm}^{-3}$ ) >  $C_{AR}$  ( $1.26 \text{ g cm}^{-3}$ ) > ORG ( $1.22 \text{ g cm}^{-3}$ ) >  $C_{BIO}$  ( $1.18 \text{ g cm}^{-3}$ ), 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

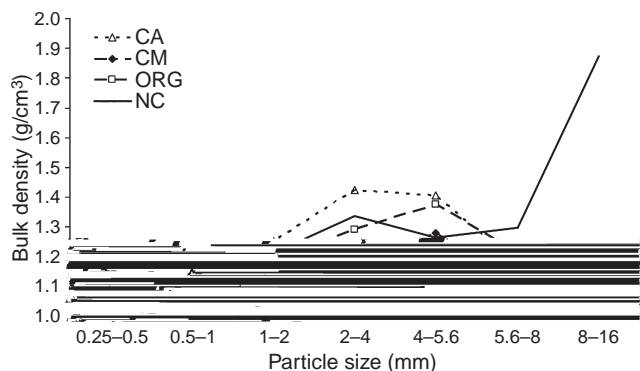


Fig. 2 Bulk density distributions.

cultivated samples while macroaggregates become more consolidated over time in the non-cultivated soil.

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

Tab 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

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 ( $11.61 \mu\text{m}$ ) >  $C_{BIO}$  ( $8.86 \mu\text{m}$ ) > ORG ( $6.99 \mu\text{m}$ ) >  $C_{AR}$  ( $4.81 \mu\text{m}$ ). 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 run-

$P = 0.05$ ), 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 microaggregates 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

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



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