The relationship between soil quality and crop productivity across three tillage systems in south central Honduras

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Abstract. *Agricultural soil quality (SQ) research has focused on the influence of individual soil properties, particularly those related to soil organic matter (SOM), on soil processes such as water movement and retention, and nutrient cycling. However, few studies have assessed the influence of these SOM-related properties on crop productivity, particularly under different management systems. Furthermore, agricultural SQ research in tropical regions is limited. The objectives of this study were, for a tropical site, to determine (1) the relationship between selected soil characteristics and resulting soil functional properties such as aggregate stability and porosity, and (2) the relationship between SQ indicators and productivity of corn under three different tillage systems. Twelve plots were randomly demarcated in three adjacent fields under different tillage systems. Profiles were described by augering and the surface soil (0–7.5 cm) was sampled just prior to crop harvest and analyzed for texture, standard soil tests (pH, available P, K, Mg and Ca) and SQ parameters including total N, total and active fraction C, porosity and aggregate stability. Corn dry grain* m^{-2}*, above-ground crop dry matter* m^{-2}*, and dry grain per plant was measured in each plot. Soil C parameters were highly predictive of macroaggregate stability and soil porosity across different tillage systems. Macroaggregate stability and soil C (particularly active C oxidizable by 0.025 m* $KMnO_4$*) were highly correlated with crop productivity across tillage systems. These findings suggest that soil C in the surface layer, especially the active C fraction, markedly affected the productivity of this tropical soil through its influence on soil structure.*

Key words: active soil carbon, minimum tillage, no-till, permanganate-oxidizable carbon, soil aggregate stability, soil organic matter, soil porosity, soil quality indicators, tropical agriculture

Introduction

The quality or health of a soil refers not only to its lack of degradation or contamination, but also to its overall fitness, or effectiveness for supporting plant growth, managing water and responding to environmental stresses (Lewandowski et al., 1999). In recent years soil quality (SQ) research has focused on the linkages among: (1) management practices and systems; (2) observable soil characteristics; (3) soil processes; and (4) performance of soil functions (Lewandowski et al., 1999). Soil organic matter (SOM)-related properties have been shown to serve as good SQ indicators (Arshad and Coen, 1992; Islam and Weil, 2000; Kennedy and Papendick, 1995; Larson and Pierce, 1994; Wander and Bollero, 1999). Soil organic matter is associated with reduced erosion and runoff, and improved infiltration, movement and retention of water in soil; soil aggregation; and nutrient cycling (Greenland and Szabolcs, 1994; Woomer and Swift, 1994). A microbially active C fraction, although a small component of the total SOM, plays a particularly important role in maintaining SQ (Weil, 1992). Active soil C regulates nutrient cycling (Gunapala and Scow, 1998) and serves as an agent for building soil structure (Tisdall and Oades, 1982).

Research during the past 50 years has placed much emphasis on the importance of mineral nutrients for crop productivity, with notably less research on the crop productivity effects of SOM management. While the beneficial effects of SOM management on soil functions have been well researched (Karlen et al., 1992; Seybold et al., 1996), it is more difficult to demonstrate the influence of SOM on crop yields (Lucas et al., 1977; Strickling, 1975). One reason for this difficulty is that SOM levels are usually related to climate, topography and soil texture. Where crop productivity is compared across widely differing soils, the yield effects of these environmental factors tend to obscure or be confounded with those due to SOM levels themselves. Furthermore, where differences in SOM are achieved by imposing treatments such as different rotations, tillage systems or rates of manure application, the SOM effects on crop yields are usually confounded with other effects of these treatments, such as the nutritional effect of high N legume residues, the water and temperature alterations due to surface mulch, and the effect of N and other essential elements contained in applied manure. Strickling (1975) was successful

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in isolating the effect of organic C by imposing various crop rotations for two decades to alter soil C levels and then treating all plots alike in the final years (including adequate mineral fertilization) to assess the residual effects of the build-up or depletion of soil C. He found that SOM levels accounted for 82–84% of the variation in corn (*Zea mays* L.) yield regardless of level of N fertilization. He attributed the SOM effects on yield to enhancement of water infiltration resulting from improved aggregation.

The majority of SQ research has been conducted on temperate region soils; SQ research on tropical soils is much more limited (Ericksen and McSweeney, 2000; Palm et al., 1996). Woomer et al. (2001) reported that total organic C in soils accounted for 25% and active fraction C (particulate organic matter) accounted for 59% of the variation in corn yields on a highly weathered soil in the highlands of central Kenya.

The objectives of this study were to determine, for a tropical site: (1) the relationship among selected individual soil C characteristics and resulting soil functional properties, such as aggregate stability and porosity; and (2) the relationship between SQ indicators and productivity of corn (‘Guayape’) across three different tillage systems.

Materials and Methods

Study site

Soil quality properties and corn yields were measured in three adjacent 2.5–ha fields that had been converted from an 8–ha grass pasture using three different tillage systems. The fields were located on Potrero #3 in the Las Vegas section of the Pan American School of Agriculture (EAP) in Zamorano valley. This valley is located in the Department of Francisco Morazán, south central Honduras, at 13°55′N latitude and 86°57′W longitude, and at approximately 800 m above sea level. The average annual rainfall is 1132 mm and the average annual temperature is 18°C (Jirón Estrada, 1997; SPCP, 1989). Soils in the Zamorano valley formed on alluvial deposits that date back to the Quaternary period (11,000–1.7 million years ago) and contain sediment derived from igneous and basaltic rocks originating in the surrounding mountains (IGN, 1996; SPCP, 1989). The soil at the experimental site is classified in the Buffalo series: a medium-fine, mixed, isohyperthermic Vertic Haplustalf (USDA taxonomy) with poor drainage and a dark brown surface horizon approximately 20 cm thick (SPCP, 1989). The site is nearly level (0–2% slope) and prone to flooding. Borings were made with a bucket auger at seven locations in a transect across the Potrero fields and a sandy loam (10–15% clay) E horizon was observed to have an upper boundary varying from 18 to 33 cm. A Bt horizon with expanding-type clays (45–50% clay) began at 25–38 cm in depth. A few iron and manganese nodules were observed at depths greater than 34 cm, but without any discernable pattern along the transect. Soil pH increased with depth from 5.8–6.0 in the Ap horizon to 7.0–8.0 in the Bt.

Experimental design and sampling scheme

The site was in pasture dominated by stargrass (*Cynodon nlemfuensis* Vanderyst) for 25 years before it was converted to crop production beginning in 1995 (P. Paz, EAP, personal communication, January 2000). Before crops were planted, the field was divided into three smaller fields (approximately 2.5 ha each), and a composite soil sample was taken from each field to a depth of 30 cm. All three fields were then subsoiled to a depth of 24 cm to break up compacted layers attributed to trampling by cattle. Subsequently, glyphosate [*N*-(phosphonomethyl)glycine] was applied to the entire experimental area at a rate of 900 g a.i. ha^{-1}. Fifteen days later, the three fields were prepared for cropping by no-tillage (direct seeded), minimum tillage (chisel plow) and conventional tillage (moldboard plow and disc) methods, respectively. The no-till field was located nearest the road and was at a slightly higher elevation than the field under conventional till, which was nearest a stream. The field under minimum till was situated between the no-till and conventional till fields. Corn was mechanically planted on each field at 53,000 plants ha^{-1} in 1995, 1996 and 1998. Sorghum [*Sorghum bicolor* (L.) Moench] was planted in 1997. Corn stover was left in the field after grain harvest, but sorghum residue was removed for silage. The three fields were left fallow from November to June each year, resulting in substantial growth of volunteer stargrass that was killed by annual use of glyphosate before planting. For the 1998 cropping season, paraquat (1,1′-dimethyl 4,4′-bipyridinium), alachlor [2–chloro-*N*-(2,6–diethylphenyl)-*N*-(methoxymethyl)acetamide] and atrazine [6–chloro-*N*-ethyl-*N*′-(1–methylethyl)–1,3,5–triazine–2,4–diamine] herbicides were applied at the time of planting, at rates of 1200 g a.i. ha^{-1}, 960 g a.i. ha^{-1} and 252 g a.i. ha^{-1}, respectively. Diammonium phosphate fertilizer was applied at planting (29 kg N ha^{-1} and 32 kg P ha^{-1}) and urea was applied 1 month after planting (84 kg N ha^{-1}).

In October 1998 four 4 × 2–m sampling plots were demarcated at random locations within each of the three fields, for a total of 12 sampling units. Since tillage methods were spatially segregated into adjacent fields, there were no independent replicates within a tillage method (Hurlbert, 1984). Such systematic experimental designs risk introducing bias to treatment effects (e.g., a gradient in soil depth or drainage), which may lead to type I errors (Hulbert, 1984; Yates, 1939). Therefore, inferences about effects of tillage methods cannot be made from this study with a known level of statistical confidence.

Data collection

The surface soil in each plot was described and 12 cores, sampled to a depth of 7.5 cm, were combined to make a composite sample for each plot. Soils were sampled in 1998 just prior to harvest, when the soil was least likely to have been recently disturbed. This sampling depth was chosen as the layer in which major differences among tillage practices generally first occur (Mielke et al., 1986). Soil parameters measured in the field were depth of A horizon, color (A horizon and underlying horizon) and texture by feel (A horizon and underlying horizon).

Laboratory analysis of surface soil samples included the following tests. Anthrone-reactive carbohydrate C (ARC) was measured on fresh samples using a modification of Brink et al. (1960), whereby the soil was extracted with $0.5\,M$ K_2SO_4 after microwave irradiation (Islam and Weil, 1998). Carbon oxidizable by dilute permanganate (C_{OXID}) was determined by shaking 1 g air-dried soil in 20 ml of $0.025\,M$ $KMnO_4$ for 15 minutes, followed by centrifugation to clear the supernatant, and measurement of light absorbance at 550 nm [modified by Islam and Weil (1999), from the $0.33\,M$ $KMnO_4$ method of Blair et al. (1995)]. Total C (C_{TOT}), total N (N_{TOT}) and total H (H_{TOT}) were determined by high temperature combustion using LECO CHN-600 analyzer (LECO Corp., St. Joseph, Mich.). The stability of 1–4 mm macroaggregates (AGG) was determined by a modification of Kemper and Rosenau (1986) method. The University of Maryland Soil Testing Laboratory determined Mehlich I extractable P, K, Mg and Ca. Particle size distribution was determined by a pipette method (Weil, unpublished data); porosity was calculated from the bulk density of 12 cores; and pH (in water and in $1\,M$ KCl) was measured using a combination glass/calomel electrode. Effective cation exchange capacity (ECEC) was estimated as the sum of the mol charge kg^{-1} from K, Mg and Ca, plus exchangeable acidity, as measured by pH_{KCl}.

All corn stalks and ears within each 4 × 2–m plot were counted and weighed in the field. Three plants and three ears were also randomly selected from each plot and the fresh and dry weights were obtained. Crop productivity was calculated as dry grain m^{-2}, above-ground crop dry matter m^{-2} and dry grain per plant.

Statistical methods

SYSTAT statistical software (SPSS, 1997) was used for all statistical analyses. Soil properties were plotted against each other and against crop productivity variables to determine the nature of these relationships. Linear regression was used to determine the relationship among three measures of soil C. Forward stepwise multiple regression was used to determine possible combinations of soil variables most associated with soil macroaggregate stability and soil porosity. The significance level for each variable to enter the model and stay was 0.05. The best-fit line was then determined between the soil variables that remained in the model and the soil functional properties. Pearson correlation and linear regression were used to express relationships between individual soil properties and crop productivity. Forward stepwise multiple regression was used to test a suite of soil variables against crop productivity, with the aim of developing a soil quality model that would best predict crop yield. The significance level for each variable to enter this model was 0.15 and the significance level to stay in the model was 0.05.

Table 1. Soil properties (0–7.5 cm layer) and corn yields in 1998 in three adjacent fields cropped for 4 years under different tillage systems (mean ± standard error, $n = 4$).

Measured variable	Upper field under no tillage	Middle field under minimum tillage	Lower field under conventional tillage
Soil properties		Mean ± standard error	
ARC (g kg^{-1} soil)	0.228 ± 0.01	0.157 ± 0.004	0.101 ± 0.007
C_{OXID} (g kg^{-1} soil)	2.17 ± 0.140	1.54 ± 0.080	1.23 ± 0.054
C_{TOT} (g kg^{-1} soil)	35.6 ± 1.51	24.4 ± 0.85	17.9 ± 0.40
ARC:C_{TOT}	0.64 ± 0.008	0.65 ± 0.02	0.56 ± 0.05
C_{OXID}:C_{TOT}	6.1 ± 0.2	6.3 ± 0.2	6.8 ± 0.2
AGG (%)	14.1 ± 2.3	4.72 ± 0.28	3.54 ± 0.24
C_{TOT}:N_{TOT}	10.9 ± 0.12	10.7 ± 0.20	10.4 ± 0.21
N_{TOT} (g kg^{-1} soil)	3.27 ± 0.17	2.28 ± 0.05	1.73 ± 0.02
P (kg ha^{-1})[1]	116.5 ± 10.7	99.26 ± 11.6	83.75 ± 39.8
K (kg ha^{-1})[2]	390.4 ± 28.0	291.2 ± 20.7	229.6 ± 20.7
Ca (kg ha^{-1})[3]	2390 ± 640	2339 ± 783	2296 ± 204
Mg (kg ha^{-1})[4]	303.7 ± 20.0	293.1 ± 20	347.3 ± 11
pH_{water}	5.25 ± 0.087	5.30 ± 0.058	5.38 ± 0.14
pH_{KCl}	4.72 ± 0.11	4.75 ± 0.065	4.58 ± 0.12
ECEC (cmol kg^{-1})	6.91 ± 0.47	6.64 ± 0.59	6.38 ± 0.50
Porosity (%)	64.8 ± 0.77	61.5 ± 1.22	59.2 ± 1.3
Corn properties			
Grain (g m^{-2})	537 ± 74	333 ± 64	207 ± 33
Dry matter (g m^{-2})	2014 ± 273	1503 ± 152	1244 ± 222

[1] P test levels are as follows: low = 14–29, medium = 30–49, high = 50–99, very high = >99.

[2] K test levels are as follows: low = 34–78, medium = 79–149, high = 150–299, very high = >299.

[3] Ca test levels are as follows: low = 0–480, medium = 481–963, high = 964–1926, very high = >1926.

[4] Mg test levels are as follows: low = 40–78, medium = 79–139, high = 140–297, very high = >297.

[Ranges calculated from Coale (1996), as determined for soils in the south-eastern US.]

For the soil properties: ARC = anthrone-reactive carbohydrate C, C_{OXID} = C oxidizable by dilute permanganate, C_{TOT} = total C, AGG = 1–4 mm soil macroaggregates, N_{TOT} = total N, and ECEC = effective cation exchange capacity.

Results and Discussion

Relationships among soil properties under three tillage systems

Soil properties and corn productivity measures for each of the three fields are presented in Table 1. Surface soils in the upper field under the no-till system were higher in SQ parameters and macronutrients compared to the middle and lower fields under the minimum and conventional tillage systems, respectively. Similar trends were observed with respect to crop productivity among the fields. These differences in SQ and crop productivity cannot be strictly ascribed to tillage, however, because true replication of tillage treatments and proper baseline data were lacking. Instead, they could have resulted from subtle soil drainage differences or other pre-existing factors that we failed to observe.

The active soil C fraction (as measured by C_{OXID} and ARC) was highly correlated with C_{TOT} across all three fields (Fig. 1). The no-till field was highest in both total C and active C, while the conventional till field was lowest in both total and active C. The strong correlation between the active C fractions and C_{TOT} across a range of values suggests that the change in C_{TOT} resulted from proportional changes in both the active and passive C fractions. This interpretation is supported by the nearly constant ratios of C_{OXID} or ARC to C_{TOT} across fields. In contrast, other researchers (e.g., Cambardella and Elliott, 1992), working in temperate regions, have reported that cultivation of grassland soils has impact primarily on the active C fractions, reducing the ratio of active fraction C to total C even as total C declines. The C content differences in the upper 7.5 cm among fields may have been partially due to differences in the extent to which the three tillage systems mixed the high C surface layer with the lower C soil below.

It was hypothesized that active C levels, as measured by C_{OXID} and ARC, would explain much of the variability in macroaggregate stability across the three fields. Forward stepwise multiple regression was used to examine possible combined effects on macroaggregate stability of the following soil properties: C_{OXID}, ARC, C_{TOT}, N_{TOT}, P, K, pH_{KCl}, Ca and Mg. While each of the first four variables listed exhibited a significant correlation with macroaggregate stability, C_{OXID} had the highest correlation coefficient and was the only variable found to remain in the final model for aggregate stability ($F = 50.6$, $P < 0.0001$). This result supports the role of the labile C components in macroaggregation and the value of C_{OXID} as a measure of active C.

The best-fit model of the relationship between C_{OXID} and macroaggregate stability (Fig. 2a) suggests that C_{OXID} below a threshold level of approximately 1750 g kg^{-1} did not appear to have an effect on macroaggregate stability, while small increases in C_{OXID} above this threshold level were reflected in up to a fourfold increase in macroaggregate stability. Macroaggregate stability was highest in the no-till field and lowest in the conventional till field, but overall macroaggregate stability levels were relatively low across all three fields. Low levels of macroaggregate stability are typical of soils dominated by 2:1 expanding-type clays. It is not known if the relationship between macroaggregate stability and C_{OXID} observed in this study exists in more strongly aggregated soils.

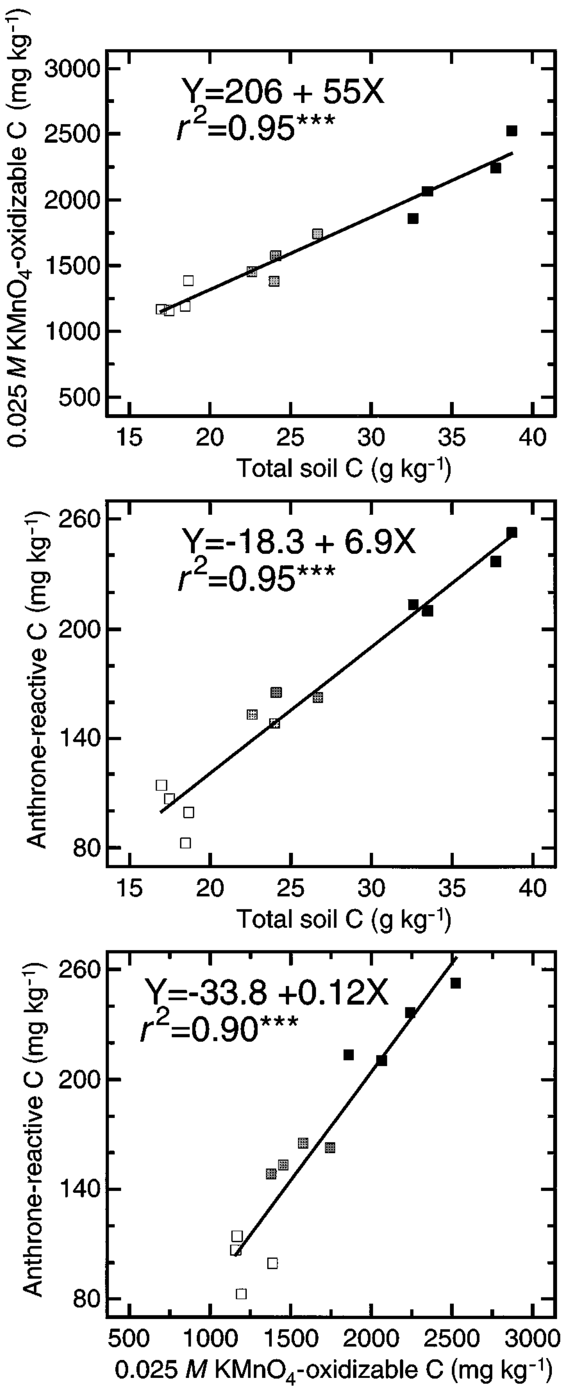

Figure 1. The relationships among three measures of soil C across three tillage systems (white = conventional till, gray = minimum till, black = no till); $n = 12$. ***Significant at the 0.001 level of probability. Note that the axes do not begin at zero.

Using forward stepwise multiple regression, C_{TOT} was the only measured soil variable that remained in the final model to predict soil porosity ($F = 23.1$, $P < 0.001$). This finding also supports the idea that soil C is an important factor influencing

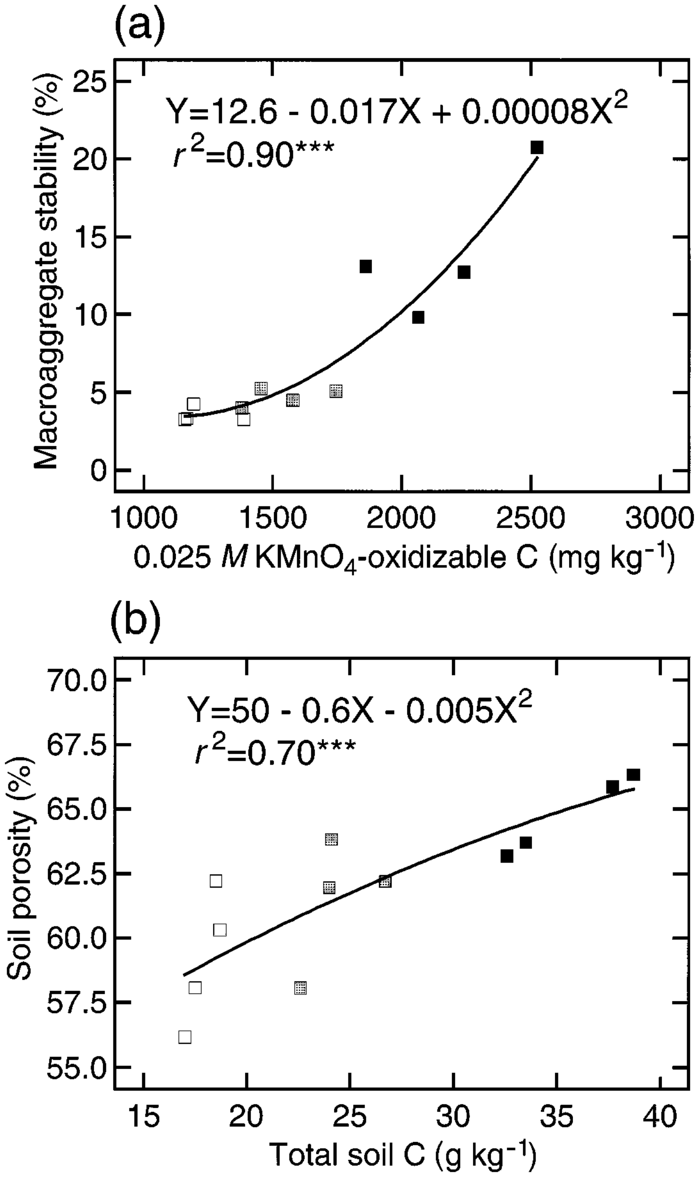

Figure 2. The best-fit models for permanganate-oxidizable soil C and macroaggregate stability (a) and total soil C and soil porosity (b) across three tillage systems (white = conventional till, gray = minimum till, black = no till). Note that the axes may not begin at zero.

soil functional properties such as porosity (and its inverse, bulk density). The relationship between C_{TOT} and porosity fits a quadratic model, as illustrated in Figure 2b. Both macroaggregate stability and porosity in the upper 7.5 cm of soil have the potential to affect crop productivity through their influence on water infiltration and aeration.

Relationship between soil quality and crop productivity under different tillage systems

Comparison of individual soil properties with crop productivity revealed that C-related soil properties were highly correlated with corn grain yield across three tillage systems (Table 2). Macroaggregate stability was the soil variable most closely correlated with yield, but ARC, C_{OXID} and C_{TOT} were also highly correlated. Similar trends were observed between soil properties and above-ground crop dry matter. Both the grain and stover had matured before Hurricane Mitch arrived in late October/early November 1998; however, as harvest took place under wet, muddy conditions following flooding from the hurricane, the stover data may have been affected by soil contamination. The grain, on the other hand, was held in the ears high enough off the ground to escape any soil contamination.

Table 2. Pearson correlation coefficients (r) between soil and crop yield variables across three tillage systems (n = 12).

	Measures of crop productivity	
Measured soil property[1]	Grain yield (g m^{-2})	Crop dry matter (g m^{-2})
AGG (%)	0.87****	0.76***
C_{OXID} (g kg^{-1})	0.86****	0.76***
C_{TOT} (g kg^{-1})	0.83***	0.72**
N_{TOT} (g kg^{-1})	0.83***	0.73**
K (kg ha^{-1})	0.83***	0.81***
ARC (g kg^{-1})	0.81***	0.70*
pH ($pH_{water} - pH_{KCl}$)	0.75**	NS
C_{TOT} :clay	0.68*	0.69*
Porosity (%)	0.64*	0.66*
pH_{KCl}	NS	0.66*
Ca (kg ha^{-1})	NS	NS
ECEC (cmol kg^{-1})	NS	NS
C_{TOT}:N_{TOT}	NS	NS
P (kg ha^{-1})	NS	NS
Mg (kg ha^{-1})	NS	NS
pH_{water}	NS	NS

*,**,***,**** Significant at the 0.05, 0.01, 0.001 and 0.0001 levels of probability, respectively.

[1] See Table 1 for description of soil properties.

Properties relating to soil fertility were less correlated or unrelated to corn yields. Since all three fields in this study had relatively high N, P and K availability, these nutrients were not expected to be limiting factors in plant growth or to play major roles in yield variability. The correlation between yield and K shown in Table 2, rather than suggesting that K caused the higher yields, is more likely to be a result of vegetative 'pumping' of K (Vilela and Ritchey, 1985) that may have brought additional K to the soil surface, where it would have remained relatively undisturbed in the no-till plots.

The following soil variables were included in a forward stepwise multiple regression model on grain yield: C_{TOT}, N_{TOT}, P, K, pH_{KCl}, Ca, Mg, AGG, C_{OXID} and ARC. Macroaggregate stability (AGG) was the only variable found to be significant and remain in the final model ($F = 31.5$, $P < 0.0001$). Thus, macroaggregate stability appeared to be the best predictor of soil productivity under three tillage systems. Furthermore, Figure 3 shows that there is a positive relationship between AGG and grain yield, and between C_{OXID} and grain yield. The data confirm therefore that active soil C, and related functional soil

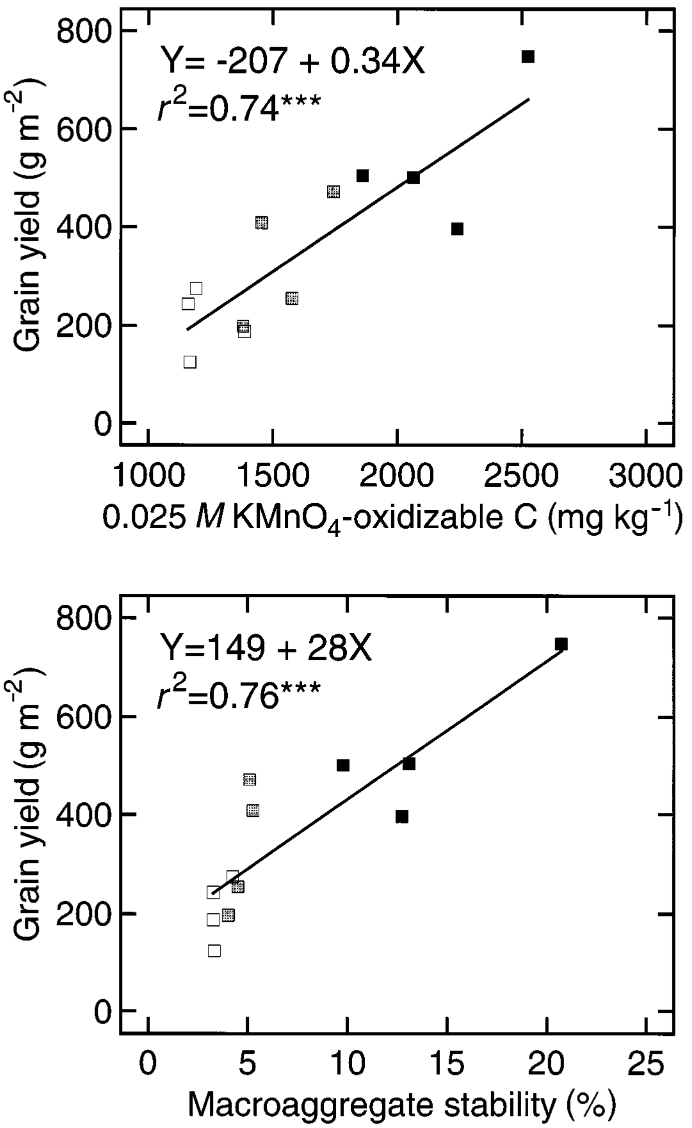

Figure 3. The relationship between soil quality properties and corn grain yield across three tillage systems (white = conventional till, gray = minimum till, black = no till, $n = 12$). ***Significant at the 0.001 level of probability. Note that the axes may not begin at zero.

variables such as soil aggregation, play important roles in improving SQ for crop production. We speculate that increased C_{OXID} may have influenced corn yields through its effect on aggregation, which in turn may have improved the capture of rainwater. Unfortunately, it is not possible to determine from the data obtained whether improved soil quality enhanced corn yield, or whether high plant production caused the improvements in soil C–related properties.

Conclusions

Soil C was strongly correlated with two soil functional properties, i.e., macroaggregate stability and soil porosity across fields under three different tillage systems. Soil C, as well as macroaggregate stability, also showed a strong relationship with crop productivity across the three tillage systems. These findings suggest that soil C, and particularly the active soil C fraction, is important to soil functioning and plant productivity. Soil quality parameters and crop productivity were higher in the upper field under the no-till system, compared to the other two tilled fields, but lack of replication did not permit a statistical comparison of tillage effects on soil and crop variables. Properly designed, well-replicated, long-term experiments would have great value in promoting knowledge of soil quality under tropical conditions. Such experiments may also provide greater opportunities for international collaborative research on sustainable land management techniques and systems appropriate for the tropics.

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