Short-term tillage practices on soil organic matter pools in a tropical Ultisol

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Abstract. In tropical regions, pasture establishment involves tillage operations. Adoption of conservation tillage practices could result in lower costs and in improved soil quality by decreasing soil organic carbon (SOC) losses. This study investigated the effects of 3 tillage practices on the establishment of Brachiaria decumbens and on the total SOC and soil organic nitrogen (SON) content and its fractions in an Ultisol from the humid mountain zone of Puerto Rico that was previously under pasture. The treatments evaluated were no-tillage, minimum tillage, and conventional tillage (CT). At 120 days after planting (DAP), plant cover and density was improved in the CT treatment compared with the other treatments. At 180 DAP, there were no significant differences in the SOC, SON, aggregate size distribution, distribution of C within aggregate size classes, and labile C physical fractions among tillage treatments. Approximately 60% of the total SOC associated with aggregates was found within macroaggregates. About an equal proportion of the particulate organic matter (POM) was associated within aggregates and nonaggregate-protected free light fraction, and these were not affected by tillage management. Lower amounts of C mineralised after disruption of macroaggregates containing POM with high C/N ratio was probably due to immobilisation of the more labile protected C (iPOM). Labile forms of C were greater in macroaggregates than in microaggregates, yet comprised a lower proportion of total SOC, suggesting that macroaggregates have a greater proportion of C physically protected from microbial attack. The results indicate that there are no short-term changes in the tendency of the soil to lose C and N as a result of tillage practices for the establishment of pastures in this soil.

Additional keywords: soil organic matter fractions, soil tillage practices, soil aggregates, soil organic matter protection.

Introduction

High animal stocking density and poor soil and pasture management often deteriorate the pasture production systems used for meat cattle grazing in the mountainous zones of Puerto Rico. The high costs of pasture establishment due to soil preparation and seeding by stem sections (estimated at US$1700/ha) are of little incentive for the meat production industry of Puerto Rico, and only dairy farmers with greater economic advantage can support the costs (D. Cianzio, pers. comm.). Another factor that discourages the meat cattle producers to improve and renovate pastures established in Oxisols and Ultisols is the intensive preparation that these soils require (Vicente-Chandler et al. 1983; Tergas et al. 1988). Studies in Latin America indicate that minimum tillage techniques for pasture establishment reduce costs and protect the soil from erosion and other degradation processes (Hernández et al. 1990; Serrano and Dias-Filho 1991).

In conventional pasture planting systems, disc- and mouldboard plowing techniques lift, turn, and mix soil layers with the destruction and burial of above-ground herbaceous vegetation. In this process the residue decomposition is accelerated and there is increased nutrient availability from residues and organic matter oxidation (Calderon et al. 2001). Tillage also results in partial aggregate destruction and concomitant organic matter loss (Six et al. 1999; Wright and Hons 2005). Organic matter losses from soils worldwide contribute to increased atmospheric CO2 concentrations (Lal et al. 1998). In the highly weathered Ultisols and Oxisols, organic matter is a major determinant of soil cation exchange capacity, and its reduction leads to a decrease in...
the nutrient and water retention capability and lower soil fertility. If minimum tillage systems are successful in the establishment and renovation of pastures in these soils, this could improve the sustainability of the soil-plant system due to organic matter preservation.

Most of the carbon (C) losses following soil disturbance such as tillage originate from the active and slow pools, which comprise the biologically defined soil organic matter pools described as active (labile), slow (partially labile), and passive (stable) (Jenkinson and Rayner 1977; Jenkinson 1990; Duxbury and Nkambule 1994). The C pools are relative concepts based on the rate of decomposition of particular constituents and are more related to biological function than to particular soil chemical C constituents. For example, the active fraction consists of live microorganisms (microbial biomass), microbial products, and unprotected chemical constituents such as proteins and polysaccharides with a turnover time of a few weeks or months. The slow fractions are more resistant to decomposition due to partial physical and chemical protection with a longer turnover time (Theng et al. 1989). The passive organic constituents include humic substances and other macromolecules that are intrinsically resistant against microbial attack due to chemical recalcitrance, physical protection by adsorption on mineral surfaces, or entrapment within soil aggregates (Gregorich et al. 1997). Biological separation of soil organic C (SOC) empirically separates labile from recalcitrant forms by allowing microbes to mineralise C under controlled conditions with the most labile C mineralised first with recalcitrant C mineralised later.

Pools of SOC can also be fractionated using physically based models because organic C is protected within and between aggregates (Cambardella and Elliot 1992; Six et al. 2000; Snyder and Vázquez 2004). In its simplest case, there is a free light fraction (LF) of labile C between the aggregates and intraggregate organic matter within macroaggregates (POM) (Cambardella and Elliot 1992; Six et al. 1998). The LF may be more related to residue input rates and soil environmental conditions and the iPOM more related to aggregate turnover, which is strongly affected by tillage management (Six et al. 1998). Aggregate hierarchy levels of formation occur in which the intramacroaggregate POM facilitates the binding of microaggregates into macroaggregates, which in turn affects the variation in the accessibility of soil microorganisms to SOC that leads to pools which differ in stability and dynamics. For example, in relatively undisrupted systems such as no-tillaged agricultural and native systems, the greatest C concentration is usually found in the small macroaggregate size class (250–2000 µm), with C in this fraction being most affected by cultivation (Ihaere et al. 1994a; Cambardella and Elliott 1994). Indianisation of SOC within aggregate size classes and physical fractionation of POM permits evaluation of how aggregation under soil management systems contribute to the accumulation and loss of organic matter.

Studies in tropical Latin America demonstrate the high potential of grasses of the genus Brachiaria to restore degraded pastures (Serrano and Díaz-Filho 1991). In Puerto Rico, excellent results have been reported with regards to Brachiaria persistence and adaptation in diverse agroecologic systems (Vicente-Chandler et al. 1983; Yazman et al. 1983; Tergas et al. 1988a). Due to the diversity in agroecologic systems in Puerto Rico and throughout the tropics, there is a need to evaluate minimum tillage practices on pasture establishment with the goal of developing a more sustainable use of soil-plant resources. The objective of this study was to evaluate the short-term effects of tillage practices on the establishment of B. decumbens and organic C in the soil. Also, we used a combination of biologically defined organic matter compartments with physically based methods to assess the short-term effects of tillage practices on aggregate size distribution and C within aggregates, and organic matter pools within aggregates in an Ultisol of the central humid mountainous zone of Puerto Rico.

Materials and methods

Three tillage treatments were evaluated in an acid Ultisol of the Corozal series (very-fine, parasepilu, isohyperthermic Typic Hapludult) in Corozal municipality, Puerto Rico (Benestohl et al. 2003). The mean air temperature during the experiment (May-September of 2003) was 23°C and rainfall during the first 30 days after planting (DAP) was scarce (<70 mm), and normal (143.2 mm) in the second month. The planting treatments evaluated were no-tillage (NT), minimum tillage (MT), and conventional tillage (CT). The NT consisted of the application of liquid glyphosate at rate of 6.5 L/ha, followed by mower cutting of the remaining material. The MT treatment consisted of the application of glyphosate followed by grass cutting and finishing with 1 pass with a disc plow. The CT treatment consisted of 2 passes with a mouldboard plow followed by 2 passes with a disc plow on separate days each, 30 days prior to planting. Field planting of Brachiaria decumbens seed was performed with a fertilizer spreader calibrated to apply the equivalent amount of 15.2 kg/ha. The seed was mixed with rice hulls at an approximate mixture ratio of 1:1 to facilitate the application. After dispersion of the seed, the fields were compacted with a heavy roller. Plant density was determined by counting the number of plants regrown in a 1-m² quadrant. Plant cover was evaluated using a 1-m² quadrant divided in 25 squares, to determine the percentage of grass covering the soil. Both quadrants were tossed 10 times each within each plot. Measurements were made 2 and 4 months after establishment.

Soil samples were taken with a auger sampler from 0 to 0.15 m depth within field plots at 180 DAP. Soil pH (1:2 soil:water) ranged from 4.87 to 5.98, extractable P ( Bray-I ranged from 8 to 22 mg/kg, and exchangeable Ca, Mg, and K ranged from 7.64 to 10.5, 0.53 to 0.73, and 0.81 to 1.1 cmol/kg, respectively, and reflect the previous history of the fields, which were under intensive pasture production and had received lime and fertiliser at recommended rates (Vicente-Chandler et al. 1983) for at least 40 years. Samples were air-dried and sieved to pass a 1-mm sieve. Part of the material was sieved to pass a 2-mm sieve and analysed for total C and N by automated combustion using a LECO CHN-2000 analyzer (Leco Corp., St. Joseph, MI) at the University of Georgia Soil Testing Laboratory (Nelson and Sommers 1982). Aggregate size separation was performed on the <4.75-mm fraction, by wet sieving air-dried soil (100 g soil) through a series
of sieves (2000, 250, and 53 μm) (Elliott 1986; Cambardella and Elliott 1994). Four aggregate fractions were obtained: (i) >200μm (large macroaggregates), (ii) 250-2000μm (small macroaggregates), (iii) 53-250μm (microaggregates), and (iv) 20-53μm. The soil was added to a 2-mm sieve, and capillary wetted for 5 min at room temperature. At this time, the sieve was moved 3 cm up and down in deionised water with 50 repetitions during a period of 2 min. Material remaining on the sieve was backwashed into a container and dried at 60°C for 24h in a forced air oven and weighed. The soil water mixture that passed the sieve was poured on the next-finer sieve size and the process was repeated until the 4 aggregate size classes were obtained. Floating plant residues and roots >1 mm were removed using forceps from subsamples of the aggregate size fractions.

The soil fraction >250 μm (macroaggregates) was dried in a forced-air oven at 50°C, prior to the separation of 2 fractions from POM of the macroaggregates, which were the LF (POM between aggregate) and iPOM (POM within aggregate). The separation was conducted as described by Six et al. (2000). Briefly, 5 g of subsample was suspended in 35 mL of 1.85% cm−3 of sodium polytungstate. The suspended subsample was shaken on a reciprocal shaker and centrifuged (1250G) at 20°C. The floating material was aspirated and dried at 50°C (LF). The heavy fraction was dispersed in 0.5% hexametaphosphate, and passed through the 250-μm sieve; the material remaining in the sieve was dried (iPOM). The C and N concentration from the LF and iPOM were quantified as described previously. The values are reported on a sand-free aggregate basis. Uncrushed (Undisrupted) and crushed (Disrupted) macroaggregates were incubated for 28 days to determine the amount of C mineralised from LF and iPOM + LF, respectively.

Aggregates were sand-corrected by dispersion of 4-g portions in 10 mL sodium hexametaphosphate followed by weighing the material that remained in the 53-μm sieve. Because the concentrations of C and N can be influenced by the different proportions of sand in each size class, samples from each aggregate size classes were corrected for the sand content as:

\[
\text{Sand-free aggregate}_{\text{C, N}} = \text{aggregate}_{\text{C, N}} \times \left[1 - \left(\text{sand proportion}_{\text{macroaggregate}}\right)\right]
\]

The sand-free C concentration within aggregates (g/kg sand-free aggregate) were calculated as (Six et al. 1998):

\[
\text{Sand-free } C_{\text{macro}} = C_{\text{macro}} \times \left[1 - \left(\text{sand proportion}_{\text{macroaggregate}}\right)\right]
\]

Total labile C (C\(\text{labile}\) and 2 components of the labile C pool in macro- and micro-aggregates were estimated. Total labile C (C\(\text{labile}\)) was estimated using the relationship between mineralizable C (C\(\text{min}\)) and time (t) and application of the one pool model:

\[
C_{\text{labile}} = C_{\text{initial}}(1-e^{-kt})
\]

using PROC NLIN of SAS (SAS version 8.01, SAS Institute, Cary, NC). Mineralizable C (C\(\text{min}\)) was quantified by measuring CO\(_2\)-C evolved from a 28-day aerobic incubation of macro- and micro-aggregates. Measurements were done at weekly intervals in a series 60/90 gas chromatograph (Agilent Technologies, Inc., Wilmington, DE), equipped with a Porapak Q column (250 μm mesh size) and a thermal conductivity detector (150°C). Two operationally defined components of the C\(\text{labile}\) pool are the soil microbial biomass C (iPOM) and labile polysaccharides (P\(_2\) ). The MBC pool was quantified by the fumigation incubation technique (Jenkinson and Powlson 1976), using a kEC factor of 0.45. The P\(_2\) pool was quantified in aggregates using the colourimetric procedure of Lowe (1993), which involves the heating of the soil material in a dilute acid solution followed by the colourimetric quantification of sample hydrolysates at 490 nm in a spectrophotometer. This analysis is considered to recover most polysaccharides other than cellulose and includes those polymers most active in aggregate formation. The tillage treatments were arranged in a field in a randomised complete block design with 3 replicates.

An analysis of variance was performed on measured and estimated parameters using SAS. Means separation was performed using Tukey's l.s.d. test with a significance level of P < 0.05.

Results and discussion

Pasture cover and plant density was greater with the CT treatments than NT and MT treatments (Table 1). There was poor seed germination in the NT and MT treatments and the majority of plants that grew in the conservation treatments were weeds. This may be attributed to the fact that there was reduced precipitation during the first month after planting (less than the lower limit of the 5-year recurrence interval (<45 mm)), which may have been sufficient for plant establishment and growth in the CT system but not for the NT and MT treatments. Tillage temporarily improves surface soil tilth, disrupts soil, and buries plant residues in the soil. It also seems that the seed to soil contact was better in the CT treatment than in the NT and MT treatments, a fact that might have enhanced seed germination with tillage.

There were no tillage treatment effects on total SOC, SON, and soil C:N ratios, with mean values of 30.3 g C/kg soil, 2.71 g N/kg soil, and 10.9, respectively. Aggregate size distribution, aggregate associated C, and C distribution among aggregates were not affected by tillage treatments, but were different among the different size classes (Table 2). For example, there was a greater proportion (81%) of sand-free aggregates in the macroaggregate (>250 μm) compared with the microaggregate (<250 μm) size class. The C concentrations were similar within macroaggregate size classes but the greatest proportion of C occurred in the >2000 μm size class. Approximately 58.6% of the total SOC associated in aggregates was present within the macroaggregates. The results indicate that structural transformation of this soil does not occur on a short-term basis with tillage after long-term cropping to pasture, although other studies have shown that changes in aggregate distributions and stabilities can occur prior to or after declines in total SOC are detected (Bear et al. 1994b). Lower SOC, or prolonged mechanical effects due to tillage combined with repeated wetting-drying cycles, may be needed to cause breakdown of aggregates and changes in structure (Snyder and Vázquez 2004). In this soil, a large part of the total

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plant cover (%)</th>
<th>6 August 2003 (plants/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>87.7a</td>
<td>19.39</td>
</tr>
<tr>
<td>No tillage</td>
<td>9.6b</td>
<td>3.26b</td>
</tr>
<tr>
<td>Minimum tillage</td>
<td>6.9b</td>
<td>3.16b</td>
</tr>
</tbody>
</table>
aggregate C could be protected by microbial attack by its physical isolation within macroaggregates, and by the high SOC initially present.

Tillage has been clearly shown to increase the proportion of macroaggregates at the expense of macroaggregates (Beare et al. 1994b; Six et al. 1999; Wright and Hons 2005). The lack of soil management tillage effect on aggregate size and C within aggregate size class is probably due to the fact that the fields where the experiment was located had been under intensive pasture production for at least 40 years. The root distribution, root exudates, and vegetative litterfall may have contributed to the observed aggregate stability (Snyder and Vázquez 2004). Most of the studies on the effects of tillage on aggregate size distribution are conducted in systems in which tillage practices have been practiced for a number of years (Cambardella and Elliot 1993; Beare et al. 1994b; Hernández-Hernández and López-Hernandez 2002; Wright and Hons 2005). On a short-term basis, the disruption of aggregates by tillage may be countered by a transient increase in aggregate stability resulting from the C flush in microbial activity that follows cultivation which may last at least 3 years (Beare et al. 1994a). The negative impact of tillage on aggregate size distribution may only be sufficiently observed in clayey Ultisols such as these because pasture establishment and renovation occurs only in-frequently, and once they are established they are maintained for long time periods.

The free LF-C values ranged from 0.90 to 3.9 g C/kg sand-free macroaggregates and the iPOM-C ranged from 1.9 to 3.7 g C/kg sand-free macroaggregates with tillage having an effect only in the free LF-C (Table 3). Similar though non-significant trends were observed with regard to iPOM-N and LF-N. Short-term effects of tillage of soils of sandy texture apparently expose microbes to labile substrates of low C/N ratio, increasing N availability, but do not increase C sources and nor subsequent respiration (Calderon et al. 2001). The C and N concentrations associated with the free LF and intraaggregate POM were within the range of values reported in other studies (Cambardella and Elliot 1992; Six et al. 1999). The LF-C accounted for 36–51% of the total C associated with POM, whereas LF-N was about 30% of the N associated with POM. Approximately 10–15% of the aggregate C could be protected by microbial attack by its physical isolation within macroaggregates, and by the high SOC initially present.

Table 2. Aggregate size distribution, C within aggregates and C distribution within aggregates of an Ultisol

<table>
<thead>
<tr>
<th>Aggregate size classification (mm)</th>
<th>Aggregate size distrib. (g sand-free aggregate/100 g soil)</th>
<th>Aggregate-associated C (g C/kg sand-free aggregate)</th>
<th>C distribution among aggregates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥2000</td>
<td>25.8b</td>
<td>42.1a</td>
<td>30.7a</td>
</tr>
<tr>
<td>250–2000</td>
<td>35.2a</td>
<td>38.5a</td>
<td>27.9b</td>
</tr>
<tr>
<td>50–250</td>
<td>12.6c</td>
<td>30.6b</td>
<td>22.4c</td>
</tr>
<tr>
<td>20–50</td>
<td>2.30d</td>
<td>25.9b</td>
<td>19.1c</td>
</tr>
</tbody>
</table>

Table 3. Comparison of C and N concentration (g/kg agg. sand-free) from free light fraction (LF) and intraaggregate particulate organic matter fraction (iPOM) within macroaggregates of an Ultisol under 3 tillage regimes

<table>
<thead>
<tr>
<th>Treatment</th>
<th>LF-C</th>
<th>iPOM-C</th>
<th>LF-N</th>
<th>iPOM-N</th>
<th>C/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional tillage</td>
<td>3.9a</td>
<td>0.12</td>
<td>0.24</td>
<td>21a</td>
<td></td>
</tr>
<tr>
<td>No-tillage</td>
<td>2.0b</td>
<td>0.08</td>
<td>0.19</td>
<td>20a</td>
<td></td>
</tr>
<tr>
<td>Minimum tillage</td>
<td>0.9b</td>
<td>1.9</td>
<td>0.17</td>
<td>11b</td>
<td></td>
</tr>
</tbody>
</table>

n.s.; Not significant for tillage (P > 0.05).
Soil organic matter pools in an Ultisol

Australian Journal of Soil Research

691

(Bear et al. 1994a; Six et al. 1998). Thus, aggregate protected pools of C are more labile than unprotected pools because protected pools are less exposed to microbial decay. In this experiment, crushing macroaggregates did not result in increases of C mineralised but rather, significant immobilisation appeared to occur as a result of crushing, especially in the soil under NT treatment (Fig. 1). Only in the MT treatment, after 15 days of incubation, mineralisation dominates the mineralisation-immobilisation process, which causes mineralised C in disrupted aggregate to be approximately 13% higher than undisrupted at the end of incubation.

García-Oliva et al. (2004) described that C mineralisation decreased as a result of crushing macroaggregates, whereas Elliott (1986) and Bear et al. (1994a) found that grinding aggregates of soils under native sod and soils under NT increases mineralisation of C and N which is attributed to release of organic matter previously inaccessible to attack (physical protection). It seems that in this study, the greater amount of C mineralised from the disrupted macroaggregates of the MT treatment is due to enhanced microbial activity, which is related to high N availability and mineralisation considering the lower C:N ratio of POM

Fig. 1. Cumulative C mineralised as influenced by tillage practices in disrupted and undisrupted macroaggregates of an Ultisol. * Significant \( (P < 0.05) \) difference between treatments.

Table 4. Pools of organic C (mg C/kg) represented as labile polysaccharides (PL) and microbial biomass (MBC) and total labile C as influenced by aggregate sizes in an Ultisol

<table>
<thead>
<tr>
<th>Aggregate size classification (µm)</th>
<th>PL</th>
<th>MBC</th>
<th>Total labile C</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;250 (macroaggregates)</td>
<td>94.7a</td>
<td>357.0 n.s.</td>
<td>2236.0a</td>
</tr>
<tr>
<td>&lt;250 (microaggregates)</td>
<td>64.7b</td>
<td>320.1</td>
<td>1968.5b</td>
</tr>
</tbody>
</table>

The treatment effects were not significant so that only size classification effects are presented. Within a column, means followed by the same letter are not significantly different at \( P > 0.05 \).
MBC comprising the total SOC was 0.89 and 1.1% for macroaggregates and microaggregates, respectively. The proportion of mineralisable C comprising the total SOC was 5.5 and 7.0% for macroaggregates and microaggregates, respectively. The measured MBC, mineralisable C, and proportions in our study were similar to those measured in sand-free aggregates of an Ultisol under no-tillage, conventional tillage, and native savanna of Venezuela (Hernández-Hernández and López-Hernández 2002). On the other hand, the microbial C values within aggregates in this study were higher than mean values quantified in the bulk soil of a highly degraded Ultisol under grasses (Sotomayor-Ramírez et al. 2004). Mineralisable C values were similar to values reported in an (acid) Ultisol in Venezuela by Espinoza (2004), but it was 1-fold lower than the one reported for a Mollisol in eastern Kansas, USA, under varying tillage regimes (Mikha and Rice 2004).

The pools of total SOC, labile polysaccharide C, mineralisable C, and labile non-microbial C were significantly higher in macroaggregates than microaggregates. Relationships between aggregate size and indicators of labile C have been reported (Cambardella and Elliott 1993; McLauchlan and Hobbie 2004; Mikha and Rice 2004). The increase in the labile C pools measured in this study with greater aggregates size class may be due to the physical protection of otherwise labile SOC (Six et al. 2000), and supports the idea that polysaccharides aid in aggregate formation and that as aggregates form they physically protect C (Tisdall and Oades 1982, Haynes and Francis 1993). The greater amount of total C within macroaggregates results in a proportionally greater amount of mineralisable C and suggests that macroaggregates contribute more to short-term nutrient cycling than microaggregates (Mikha and Rice 2004).

Conclusion
Since the fields where the experiment was located had been under intensive pasture production for at least 40 years, the root distribution, root exudates, and vegetative litterfall may have contributed to the observed aggregate stability. The results indicate that there are no short-term changes in the tendency of the soil to lose total organic C, nor labile fractions as a result of tillage practices for pasture establishment, after long-term cropping to pasture. Agricultural practices that maintain the soil under long-term pasture production appear to sustain the soil's ability to store C. The soil aggregates appear to be resilient to disruption by tillage, at least on a short-term basis. The partitioning of C among aggregate size classes in an acid Ultisol is shown and demonstrates that the majority of the sand-free soil mass occurs in macroaggregates and that nearly 60% of the soil C is associated with macroaggregates. About an equal proportion of the POM was associated within aggregates, and was not affected by tillage management, yet free LF-C increased as a result of tillage. Immobilisation of mineralised C due to disruption of macroaggregates was probably due to the high C/N ratio of total POM which impeded the release of the more labile protected C (iPOM). Labile forms of C were greater in macroaggregates than in microaggregates, yet comprised a lower proportion of total SOC, suggesting that macroaggregates have a greater proportion of C physically protected from microbial attack. Long-term tillage practices may need to occur before changes in SOC pools and its fractions are apparent in clayey Ultisols of the tropics.

References


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