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REGULAR ARTICLE

Aggregation and C and N contents of soil organic matter fractions in a permanent raised-bed planting system in the Highlands of Central Mexico

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Abstract Permanent raised bed planting with crop residue retention is a form of conservation agriculture that has been proposed as an alternative to conventional tillage for wheat production systems in the Central Highlands of Mexico. A field experiment comparing permanent and tilled raised beds with different residue management under rainfed conditions was started at El Batán (State of Mexico, Mexico) in 1999. The percentage of small and large macroaggregates and mean weight diameter (MWD) was significantly larger in permanent raised beds compared to conventionally tilled raised beds both with full crop residue retention (average for maize and wheat), while the percentages free microaggregates was lower. The percentages of small and large macroaggregates and mean weight diameter (MWD) was significantly larger in permanent raised beds with residue retention compared to permanent raised beds with removal of the residue (average for maize and wheat), while the percentages free microaggregates and silt and clay fraction was lower. Cultivation of maize significantly reduced the large macroaggregates, while wheat reduced the silt and clay fraction (average over all systems). Cultivation of maize reduced the C and N content of the free microaggregates compared to soil cultivated with wheat, while removal of plant residue reduced the C and N content of the silt and clay fraction compared to soil where residue was retained. The C and N content of the coarse particulate organic matter (cPOM) and microaggregates within the macroaggregates was significantly larger in permanent raised beds compared to conventionally tilled raised beds both with full residue retention, while C and N content of the cPOM was significantly lower when residue was removed or partially removed compared to the soil where the residue was retained. The δ^{13}C ‰ signatures of the macroaggregates, microaggregates, the silt and

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clay fraction, cPOM and microaggregates within the macroaggregates were not affected by tillage or residue management when wheat was the last crop, but removal of residue reduced the $\delta\ ^{13}C$ ‰ signatures of the macro-, microaggregates and microaggregates within the macroaggregates significantly compared to soil where the residue was retained. Retaining only 30–50% of the organic residue still improved the soil structure considerably compared to plots where it was removed completely. Permanent raised beds without residue retention, however, is a practice leading to soil degradation.

Keywords Wheat · Maize · Soil aggregation · Zero tillage vs. conventional tillage · Raised bed planting · Conservation agriculture · C sequestration

Introduction

Farmers in the rain fed production areas of the Central Highlands of Mexico are facing a number of constraints. As in most of the semi-arid areas of the world, the availability of soil water is the most important limitation to productivity. Crops, dominated by continuous maize monoculture, are produced using considerable tillage. Crops are planted only once each year, leaving the soil bare for most of the year as crop residues are removed. Tillage practices and lack of soil cover, together with the sloping fields lead to extensive erosion and run-off, resulting in low yields (Sayre et al. 2001; Govaerts et al. 2007a).

Planting on tilled beds holds an enormous potential for irrigated cropping systems by making them less resource-intensive and more sustainable (Sayre 2004). The system increases water use efficiency, decreases operational cost, and controls traffic by restricting machinery wheels and animals to the furrows, eliminating compaction in the seeded area. One of the next, logical steps to increase the sustainability of bed panting systems is to reduce tillage and manage plant residues from the previous crop on the surface and to reshape the beds only as needed between crop cycles (Sayre 2004). Literature on and experience with permanent raised beds is limited, especially for rain fed conditions, which predominate over irrigation practices in the Central Highlands of Mexico. However, the permanent raised bed system has shown a lot of advantages under irrigation, as reduced seed rates can be used while maintaining or even increasing yield, more efficient water utilization, less labor required for irrigation, better fertilizer management options and less-expensive mechanical weed control options (Limon-Ortega et al. 2000; Limon-Ortega et al. 2002). Therefore, in 1999, a unique long-term experiment was initiated by the International Maize and Wheat Improvement Center (CIMMYT, Int.) to compare bed planting based on extensive tillage with the formation of new beds for each succeeding crop versus an approach where beds are formed for the initial crop after a final tillage cycle and are then reused as permanent raised beds with only superficial reshaping of the furrows as needed before planting of each succeeding crop. The experiment includes permanent bed planting with tied-ridges, i.e. dikes within the furrows to prevent water run-off, compared to open furrows, and different levels of crop residue retention to determine whether those practices can improve the sustainability of the maize based cropping systems in the rain fed systems of the (sub)tropical highlands. As part of a study into the overall sustainability of these different cropping systems we wanted to investigate the effect of the different crop management practices on soil structure and organic C and N.

Soil structure is a key factor in soil functioning and is an important factor in the evaluation of the sustainability of crop production systems. Emerson (1959) defines soil structure as the size, shape and arrangement of solids and voids, continuity of pores and voids, their capacity to retain and transmit fluids and organic and inorganic substances, and the ability to support vigorous root growth and development. Soil structure is often expressed as the degree of stability of aggregates (Six et al. 2004).

Reduced aggregation is a direct function of physical disturbance due to tillage (Paustian et al. 1997), which disrupts soil aggregates mechanically and fragments roots and mycorrhizal hyphae, which are major binding agents for macroaggregates (Tisdall and Oades 1982). It has been known for many years that the addition of organic substrates to soil improves its structure (Ladd et al. 1977). Fresh residue forms the nucleation centre for the formation of new aggregates and a greater residue input stimulates aggregate formation (De Gryze et al. 2005). The return of crop residue to soil does not only increase the aggregate formation, but it also decreases the breakdown of aggregates by reducing erosion and protecting the aggregates against raindrop impact. The role of aggregation and physical disturbance induced by tillage in controlling C and N dynamics have been extensively investigated in the last decades (e.g. Elliott 1986; Beare et al. 1994; Six et al. 1998). Recent studies indicate that the macroaggregate structure exerts some physical protection on soil organic matter (Beare et al. 1994), whereas soil organic matter is mostly protected in free micro-aggregates (Jastrow et al. 1996; Six et al. 1998) and in microaggregates within the macroaggregates (Six et al. 2000; Denef et al. 2001; Bossuyt et al. 2002).

The objective of the presented study was to determine the effect of conventional tillage versus permanent raised beds, different levels of residue retention (full, partial and no retention of crop residue) and use of tied-ridges or open furrows between the raised beds on (1) the aggregate size distribution and (2) total C and N concentrations in aggregate size fractions after 6 years of rotational maize and wheat cropping.

Materials and methods

Sampling site

Soils for this study were collected from a field experiment located at the International Maize and Wheat Improvement Centre experimental station near El Batán, State of Mexico, Mexico (19°31 N, 98° 50 W, elevation 2,240 m). Mean annual temperature at El Batán is 14°C (calculated over 1990–2001) and mean annual rainfall 600 mm, with about 520 mm falling between May and October. Evaporation exceeds rainfall throughout the year and short, intense rain showers followed by dry spells typify the rainy season. The station has an average length of growing period of 152 days. The soil is classified as a Cumulic Phaeozem in the World Reference Base system (IUSS Working Group WRB 2006) and as a fine, mixed, thermic Cumulic Haplustoll in the USDA Soil Taxonomy system (Soil Survey Staff 1998). The soil is characterized by good chemical and physical conditions for farming activities. The major limitations are periodical drought, periodical water excess and wind- and water erosion. Further details of the experimental site and the effect of tillage, crop systems and rotation on yield and soil quality can be found in Govaerts et al. (2007b).

Description of the long-term field experiment

Details of the long-term field experiment can be found in Govaerts et al. (2007b). Briefly, the experiment was started in 1999 and individual plots measured 6 by 20 m with eight raised beds of 75 cm width. The experiment included two replicates in a randomized complete block design with 14 treatments of which we considered 12 treatments that include four management factors (Table 1). The first factor is tillage: (1) conventional tillage with raised beds formed after each crop (CB) and (2) zero tillage with continued reuse of the existing raised beds (re-shaped if required) (PB). The second factor is residue

Table 1 Treatments at the CIMMYT Bed-Planted Sustainability Trial in El Batan, Mexico

Treatment	Rotation	Tillage	Straw management	Tied-ridge
1	W–M	Conventional	Incorporated	No
2	M–W	Conventional	Incorporated	No
3	W–M	Permanent beds	Retained	No
4	M–W	Permanent beds	Retained	No
7	W–M	Permanent beds	Removed	No
8	M–W	Permanent beds	Removed	No
9	W–M	Permanent beds	Removed	Yes
10	M–W	Permanent beds	Removed	Yes
11	W–M	Permanent beds	Partial	No
12	M–W	Permanent beds	Partial	No
13	W–M	Permanent beds	Partial	Yes
14	M–W	Permanent beds	Partial	Yes

W wheat, *M* maize, and *Partial* maize straw removed to just below the ear; wheat straw cut by the combine removed, 20–30 cm stubble left management: (1) all above ground crop residues chopped and kept in the field whether incorporated for CB or retained on the soil surface for PB (K), (2) all crop residues removed by baling for fodder (R) and (3) crop residues partly removed (P), wheat residues cut by combine, and maize residues cut just below the ear. Tied-ridges (T) and open furrows (NT) between the raised beds are the third factor, while both phases of the maize−wheat rotation is the fourth. Standard practices in the study included the use of currently recommended crop cultivars, with maize planted at 60,000 plants ha^{-1} in two rows on top of the 75 cm raised beds and wheat planted in 20 cm rows at 100 kg seed ha^{-1}. Both crops were fertilized at the rate of 120 kg N ha^{-1} using urea with all N applied to wheat at the first node growth stage (broadcast) and to maize at the 5–6 leaf stage (surface-banded). Weed control was performed on a need basis by applying available herbicides, but no disease or insect pest controls were utilized, except for seed treatments applied by commercial seed sources. Planting of both maize and wheat depended on the onset of summer rains, but was usually done between June 5 and 15.

Soil sampling

Undisturbed composite soil samples were taken on the 27th of June, 2005 before fertilizer was applied and plants were still <10 cm. Soil samples were taken from the 0–15 cm soil layer as close as possible to the plants. Samples were air-dried and passed through a 8-mm sieve.

Water-stable aggregates

Water-stable aggregates (>2 mm, 250–2,000 and 53–250 μm) were fractionated by wet-sieving of an air-dried sub-sample of 50 g soil over 2,000, 250 and 53 μm mesh sieves (Fig. 1). Soil was spread evenly on the sieve with opening of 2,000 μm, which was immersed in water, and left for 5 min to equilibrate (slaking). Because of the strong relationship between slaking resistant aggregates and SOM (Elliott 1986), the slaking method is most often used to investigate the link between aggregates and C and N sequestration and nutrient dynamics (Six et al. 2002a). The sieve was moved up and down at a rate of 50 strokes in 2 min. Floatable plant residues were decanted off

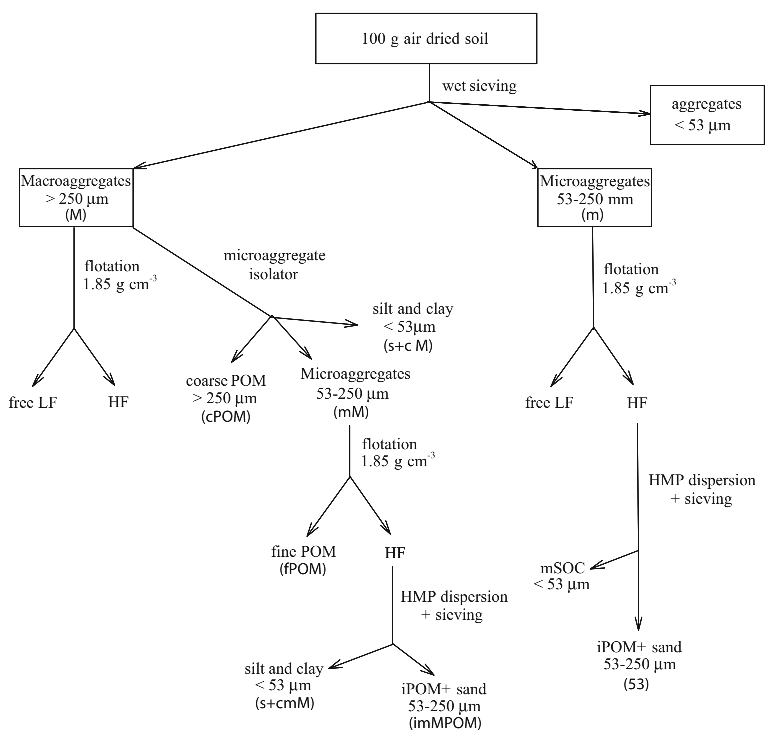

Fig. 1 Complete fractionation scheme to isolate all aggregate and particulate organic matter (POM) fractions to determine aggregate and POM C and N and gross N fluxes

during the sieving process since they were not part of soil aggregates. Particles and water that went through the 2,000 µm sieve were sieved over the 250 µm and a last time over the 53 µm sieve. All fractions were backwashed in pre-weighed aluminium pans, dried overnight in an oven at 105°C and weighed.

Mean weight diameter (MWD) of aggregates in soils collected from each plot was calculated as:

$$MWD = \sum_{i=1}^{n} X_i^{*} WSA_i / 100 \quad (1)$$

where X is the mean diameter of each size fraction (i), WSA is the proportion of total sample weight recovered in the size fraction after wet sieving (i) and n is the number of size fractions (Kemper and Chepil 1965).

Microaggregates within stable macroaggregates

A method and device (microaggregate isolator) developed by Six et al. (2000) were used to isolate the microaggregates occluded in stable macroaggregates (>250 µm); stable macroaggregates were broken up while minimizing the breakdown of released microaggregates (Fig. 1). A sub sample of 15 g oven-dried macroaggregates was slaked in deionized water for 20 min to break down large macroaggregates. Samples were subsequently immersed in deionized water on top of a 250 µm mesh screen and shaken with glass beads on a reciprocal shaker at low speed (=150 rpm) for 5 min. To ensure that microaggregates are not exposed to further disruption by slaking, water flowed continuously through the device and the microaggregates were flushed immediately through the 250 µm sieve onto a 53 µm sieve (Six et al. 2000). Once all the macroaggregates were broken up, the material on the 53 µm sieve was manually sieved at a rate of 50 strokes in 2 min to ensure that the isolated microaggregates were water-stable (Elliott 1986). Sand and coarse particulate organic matter (cPOM) were retained on the 250 µm mesh screen after breaking up the macroaggregates. All fractions were backwashed in preweighed aluminium pans, dried overnight in an oven at 105°C and weighed.

C and N contents and isotope analyses

Sub-samples of all soil fractions from the different treatments were ground. Each sample was analyzed for total C and N content and the ^{13}C isotopic composition was measured by an automated C/N analyser–isotope ratio mass spectrometer (ANCA-IRMS, Europa Scientific Integra, UK) at the UC-Davis Stable Isotope Facility.

Statistical analyses

The experiment was a randomised complete block (RCB) design. The statistical analysis was done with a one-way analysis of variance using SAS GLM procedure to test for significant differences between crops ($P<0.05$) (SAS Institute 1994). Effects of tillage were examined by comparing conventionally tilled and permanent raised beds with full residue retention. An analysis of the different variables was performed on the permanent bed treatments to look at significant influences of residue management.

All variables were then further explored under principal component analysis (PCA), through which the number of independent variables could be reduced and problems of multicollinearity solved. Variables were auto-scaled prior to PCA (Sena et al. 2002). Only components with eigenvalue > one and explaining >10% of the variability were retained (Kaiser 1960). A scree test (Cattell 1966) was performed to corroborate PC selection. A VARIMAX rotation was performed to enhance the interpretation of the uncorrelated components. All meaningful loadings (i.e. loadings>0.50) were included in the interpretation of principal components (PC).

Results

Aggregate size distribution and stability

After six years, the permanent raised beds with full residue retention had significantly greater amounts of large (>2 mm) and small (0.25–2 mm) macroaggregates compared to conventionally tilled raised beds with straw incorporated, while significantly ($P<0.05$) more free microaggregates (0.053–0.25 mm) were found in the conventional system (Table 2). The use of permanent raised beds with full residue retention increased the amount of large and small macroaggregates significantly ($P<0.05$) 2.4 and 1.3 times, respectively, compared to permanent raised beds with residue removal. When residue was removed, 1.3 times more free microaggregates were observed under

Table 2 Distribution of the soil size fractions (%) and the mean weight diameter for the different treatments of the raised bed planting sustainability trial, El Batan, Mexico

Treatment	Macroaggregates		Microaggregates	Silt and clay fraction	Mean weight diameter
	Large (%)	Small			
Tillage					
PB K	8.29 A	43.04 A	37.09 B	11.58 A	0.71 A
CB I	2.87 B	31.82 B	52.64 A	12.67 A	0.50 B
Last crop					
Maize	3.92 B	36.71 A	46.45 A	12.92 A	0.57 A
Wheat	5.94 A	36.66 A	45.42 A	11.98 B	0.60 A
Residue management					
PB K	8.29 A	43.04 A	37.09 B	11.58 B	0.71 A
PB P	6.35 AB	39.40 AB	42.56 AB	11.69 B	0.64 A
PB R	3.53 B	33.98 B	48.55 A	13.94 A	0.53 B

Values with the same letter within the same category (tillage, last crop and residue management) are not significantly different from each other ($P<0.05$)

PB K permanent beds with residue retained, *CB I* conventional beds with residue incorporated, *PB K* permanent beds with residue retained, *PB P* residue partial retained, and *PB R* residue removed

permanent raised beds as compared to residue retention within the same tillage system (Table 2). Treatments with wheat as the last crop had significantly ($P<0.05$) more large macroaggregates compared to treatments with maize as the last crop, but there was no effect of crop on small macroaggregates and microaggregates (Table 2). Tied-ridges had no significant effect on aggregate size distribution (data not shown).

Permanent raised beds with full residue retention had significantly ($P<0.05$) better soil aggregation (higher MWD) compared to conventionally tilled raised beds with residue incorporated (Table 2). A significant higher MWD was observed for permanent raised beds with full residue retention (0.71 mm) and partial residue retention (0.64 mm) as compared to residue removal (0.53 mm) (Table 2). Crop and tied-ridges had no effect on the MWD (data not shown).

Carbon and nitrogen content in water stable aggregates

There was no significant effect of crop, tillage, residue management and tied ridges on C content of the macroaggregates (>0.25 mm) (Table 3). Free microaggregates contained significantly ($P<0.05$) more C when wheat was the last crop (11.28 g C kg^{-1} free microaggregate) compared to maize (10.20 g C kg^{-1} free microaggregate). Tillage system, straw management and tied-ridges had no significant effect on C content of free microaggregates (Table 3). The silt and clay fraction contained significantly ($P<0.05$) more C when residue was fully retained in the permanent bed system compared to partial or total removal of the residue in the same tillage system. Tillage system, crop and tied-ridges had no significant effect on C content in the silt and clay fraction (Table 3).

There was no effect of tillage system, crop, straw management and tied-ridges on N content of the macroaggregates. Significantly ($P<0.05$) more N was found in microaggregates when wheat was grown as last crop (1.27 g N kg^{-1} free microaggregate, mean of all treatments) compared to maize as last crop (1.17 g N kg^{-1} free microaggregate, mean of all treatments). Management practices had no significant effect on N content of the microaggregates (Table 3). The N content of the silt and clay fraction was significantly ($P<0.05$) lower for permanent beds with residue removal as compared to the other residue management practices. There was no significant effect of tillage system, crop and tied-ridges (Table 3).

Table 3 Total C and N content (g kg^{-1}) for the soil size fractions for the different treatments of the raised bed planting sustainability trial, El Batan, Mexico

Treatment	Macroaggregates		Microaggregates		Silt and clay fraction	
	Carbon (mg kg^{-1})	Nitrogen	Carbon	Nitrogen	Carbon	Nitrogen
Tillage						
PB K	16.02 A	1.58 A	11.22 A	1.25 A	11.62 A	1.36 A
CB I	13.72 A	1.47 A	11.02 A	1.25 A	11.69 A	1.38 A
Last crop						
Maize	13.95 A	1.48 A	10.20 B	1.17 B	11.14 A	1.32 A
Wheat	14.72 A	1.55 A	11.28 A	1.27 A	11.23 A	1.32 A
Residue management						
PB K	16.02 A	1.58 A	11.22 A	1.25 A	11.62 A	1.36 A
PB P	15.62 A	1.61 A	10.70 A	1.22 A	10.84 B	1.37 A
PB R	13.57 A	1.44 A	10.26 A	1.16 A	11.03 B	1.25 B

Values with the same letter within the same category (tillage, last crop and residue management) are not significantly different from each other ($P<0.05$)

PB K permanent beds with residue retained, *CB I* conventional beds with residue incorporated, *PB K* permanent beds with residue retained, *PB P* residue partial retained, and *PB R* residue removed

Microaggregates within stable macroaggregates

The proportion of macroaggregates comprised of microaggregates occluded within macroaggregates ranged between 41% and 61% (data not shown).

Carbon and nitrogen contents in microaggregates within stable macroaggregates

The amount of C in the coarse particulate organic matter (cPOM) was significantly ($P<0.05$) higher in permanent raised beds with full residue retention (18.56 g C kg^{-1} cPOM) compared to conventionally tilled raised beds (8.56 g C kg^{-1} cPOM) (Table 4). In the permanent raised bed planting system, significantly ($P<0.05$) higher amounts of C were observed when residue was fully retained (18.56 g C kg^{-1} cPOM) compared to partial retention (9.83 g C kg^{-1} cPOM) and removal of residue (8.61 g C kg^{-1} cPOM). Crop and tied-ridges had no effect. Microaggregates within the macroaggregates contained significantly ($P<0.05$) more C under permanent raised beds with full residue retention (19.35 g C kg^{-1} microaggregate within macroaggregate) compared to conventionally tilled raised beds with residue incorporated (15.25 g C kg^{-1} microaggregate within macroaggregate). There was no effect of crop, straw management and tied-ridge on C content of microaggregates. Crop, tillage system, straw management and tied-ridges had no effect on the C content of the silt and clay fraction within macroaggregates (Table 4). The use of permanent raised beds with full residue retention for 6 years resulted in a 1.8 times higher N content of the cPOM compared to conventionally tilled raised beds with straw incorporated. The full retention of residue in permanent raised beds resulted in significantly ($P<0.05$) higher amounts of N in the cPOM (1.97 g N kg^{-1} cPOM) as compared to partial (1.20 g N kg^{-1} cPOM) or complete removal of residue (1.29 g N kg^{-1} cPOM). Microaggregates within the macroaggregates were found to contain significantly more N under permanent raised beds with full residue retention (2.10 g N kg^{-1} microaggregates within the macroaggregates) compared to conventionally tilled raised beds with residue incorporated (1.75 g N kg^{-1} microaggregates within the macroaggregates) ($P<0.05$). There was no significant ($P<0.05$) effect of crop, straw management and tied-ridge on N content of the microaggregate within macroaggregate. Crop, tillage system, straw management and tied-ridges had no significant effect on the N content of the silt and clay fraction within macroaggregates (Table 4).

Table 4 Total C and N content (g kg^{-1}) for the different size fractions after microaggregate isolation of macroaggregates for the different treatments of the raised bed planting sustainability trial, El Batan, Mexico

Treatment	cPOM		Microaggregates within macroaggregates		Silt and cay fraction of macroaggregates	
	Carbon (mg kg^{-1})	Nitrogen	Carbon	Nitrogen	Carbon	Nitrogen
Tillage						
PB K	18.56 A	1.97 A	19.35 A	2.10 A	13.82 A	1.70 A
CB I	8.56 B	1.05 B	15.25 B	1.75 B	11.87 A	1.49 A
Last crop						
Maize	10.39 A	1.39 A	15.95 A	1.81 A	13.78 A	1.60 A
Wheat	10.85 A	1.32 B	17.40 A	1.93 A	12.91 A	1.59 A
Residue management						
PB K	18.56 A	1.87 A	19.35 A	2.09 A	13.82 A	1.70 A
PB P	9.83 B	1.20 B	17.11 A	1.91 A	14.29 A	1.66 A
PB R	8.61 B	1.29 B	16.05 A	1.86 A	14.19 A	1.72 A

Values with the same letter within the same category (tillage, last crop and residue management) are not significantly different from each other ($P<0.05$)

cPOM coarse particulate organic matter, *PB K* permanent beds with residue retained, *CB I* conventional beds with residue incorporated, *PB K* permanent beds with residue retained, *PB P* residue partial retained, and *PB R* residue removed

δ ^{13}C signature of aggregate size classes and particulate organic matter fractions

The δ ^{13}C values of all soil fractions ranged from −17.43‰ to −21.96‰ (Table 5). Tillage and residue management had no significant effect on the δ ^{13}C signature of the different aggregate size classes when wheat was the last crop. However, when maize was the last crop then the δ ^{13}C signature in the macroaggregates, free microaggregates, cPOM and micro-

Table 5 δ ^{13}C (‰) signature of aggregate size classes and particulate organic matter fractions

Treatment	Macroaggregates δ ^{13}C (‰)	Microaggregates	Silt and clay fraction	cPOM	Microaggregates in macroaggregates
Wheat as last residue input					
Tillage					
PB K	−20.40 a	−20.89 a	−20.71 a	−20.49 a	−21.23 a
CB I	−20.26 a	−20.99 a	−20.83 a	−19.34 a	−21.06 a
Residue management					
PB K	−20.40 a	−20.89 a	−20.71 a	−20.49 a	−21.23 a
PB P	−21.21 a	−20.94 a	−21.09 a	−19.95 a	−21.52 a
PB R	−21.78 a	−21.30 a	−21.16 a	−20.95 a	−21.91 a
Maize as last residue input					
Tillage					
PB K	−19.37 a	−20.66 a	−20.69 a	−19.17 a	−20.99 a
CB I	−18.93 a	−20.44 a	−20.40 a	−17.43 a	−20.57 a
Residue management					
PB K	−19.37 a	−20.66 a	−20.68 a	−19.17 a	−20.99 a
PB P	−20.70 ab	−20.74 a	−21.17 a	−19.66 ab	−21.67 ab
PB R	−21.80 b	−21.80 b	−21.57 a	−21.13 b	−21.96 b

Values with the same letter within the same category (tillage, last crop and residue management) are not significantly different from each other ($P<0.05$)

PB K permanent beds with residue retained, *CB I* conventional beds with residue incorporated, *PB K* permanent beds with residue retained, *PB P* residue partial retained, and *PB R* residue removed aggregates within the macroaggregates was significantly ($P<0.05$) more negative when the residue was removed from permanent beds compared to those with residue retention.

Integration of all factors via Principal Component Analysis

Loadings for the different variables obtained after PCA and VARIMAX rotation are given in Table 6. Principal component analysis was performed using variables significantly influenced by tillage or straw management. There were five significant PCs. The PC1 explained 36% of the variability and had significant positive loadings of percentage of large and small macroaggregates in the soil, MWD and C and N content of the cPOM and significant negatives loadings of percentage of the free microaggregates, silt and clay fraction in the whole soil. The PC2, which explained an additional 24% of variability, had significant positive loadings of the C content of the silt and clay fraction and all $\delta\ ^{13}C$ values for the different fractions. An additional 12% of the variability was explained by PC3 with significant positive loadings from C and N content of the microaggregates within the macroaggregates.

Table 6 Rotated loadings on the principal components

Measurements	Principal components[a]		
	PC1	PC2	PC3
Eigenvalues	5.70	3.89	1.89
Proportions	0.36	0.24	0.12
Rotated loading on three retained components[a]			
% large macroaggregates	0.73*	−0.11	0.33
% small macroaggregates	0.92*	−0.16	−0.12
% microaggregates	−0.94*	0.18	0
% silt and clay fraction	−0.53*	−0.07	−0.12
MWD[b]	0.93*	−0.15	0.10
N in silt and clay fraction[c]	0.35	0.32	−0.20
C in silt and clay fraction[c]	0.38	0.57*	−0.09
N in cPOM[c]	0.69*	−0.17	0.23
C in cPOM[c]	0.81*	0.07	0.36
N in micro in macro[c]	0.22	0.07	0.90*
C in micro in macro[c]	0.28	0.12	0.91*
$\delta\ ^{13}C$ value of macroaggregates	−0.09	0.94 *	0.09
$\delta\ ^{13}C$ value of microaggregates	−0.31	0.71*	0.29
$\delta\ ^{13}C$ value of silt and clay fraction	−0.23	0.83*	0.30
$\delta\ ^{13}C$ value of cPOM	−0.09	0.74*	−0.38
$\delta\ ^{13}C$ value of micro in macro	−0.10	0.91*	0.06

[a] Only principal components with Eigenvalues>1 and that explain >10% of the total variance were retained

[b] MWD mean weight diameter

[c] g C or N kg^{-1} soil fraction

The PCA bi-plot of PC1 and PC2 (Fig. 2) separated the permanent raised beds with residue retention from the conventionally tilled beds along the *X*-axis and treatments with wheat as the last crop had a larger PC1 value than those with maize. The treatments with full residue retention had a positive value of PC2 while the treatment with partial and no residue retention had a negative values, clustering partial residue retention and residue removal together. The treatments with partial removal had generally larger PC1 than those with complete removal. The PCA bi-plot of PC1 and PC3 (Fig. 3) clustered conventionally tilled raised beds with all residue incorporated together with permanent raised beds with partial or no residue retention and treatments with wheat as the last crop had larger PC1 and PC3 values (Fig. 3).

Discussion

Densely populated, intensively-cropped highland areas in the tropics and subtropics are prone to erosion and declining soil fertility, making agriculture unsustainable. Permanent bed planting practices have been developed to reduce production costs while conserving resources and sustaining the environment. Numerous benefits have been observed in comparison with other planting systems (Sayre 2004). Reduced tillage in combination with residue retention on the soil surface as stubble offers advantages over conventional cropping systems by increasing water infiltration (Bruce et al. 1990; Azooz and Arshad 1996) and reducing soil erosion, thus conserving soil and water (Deen and Kataki 2003; Sisti et al. 2004). The use of crop rotations is important to break soil borne pathogen cycles and reduce weed pressure (Karlen et al. 1994).

As part of the overall sustainability evaluation of cropping systems, we evaluated the effect of the different crop management practices on soil aggregation and associated C and N pools. It is clear that tillage, straw management and crops all influence aggregate stability and C and N contents of the different soil size fractions. However, less is known about how these management practices interact to affect soil aggregation and C and N sequestration under rain fed conditions.

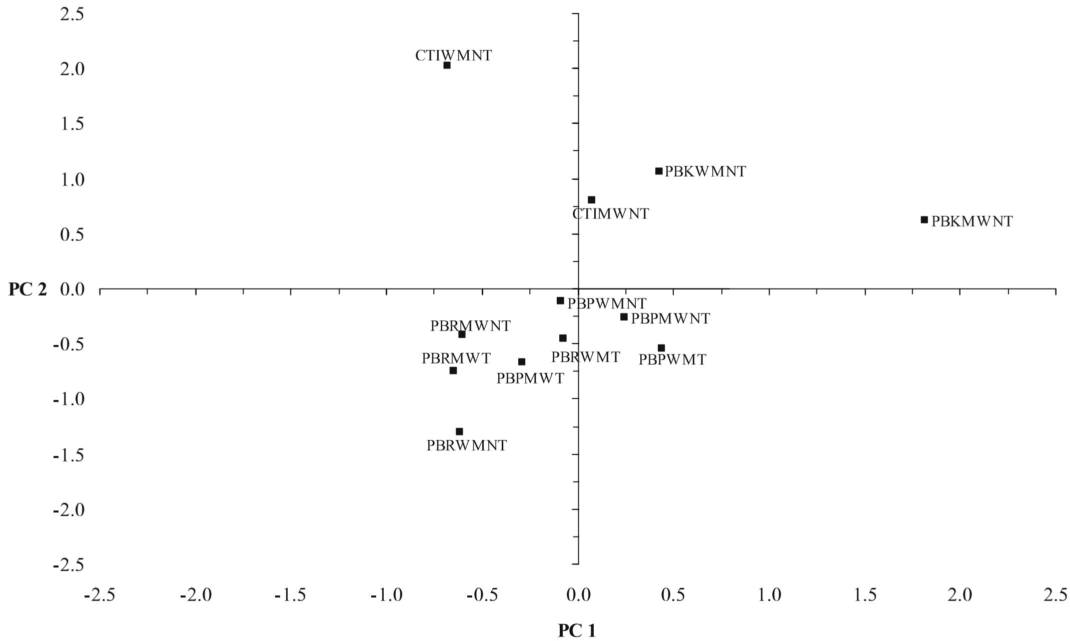

Fig. 2 Biplot of principal component 1 and 2 of the principal component analysis of all soil parameters with *M* maize; *W* wheat; *CB* conventionally tilled beds; *PB* permanent beds; *K* residue is fully kept in the field; *P* residue is partially kept in the field and partially removed; *R* residue is removed from the field; *T* with tied ridges; *NT* no tied ridges

Aggregate size distribution and stability

The amount of macroaggregates is an important parameter to understand water infiltration, soil aeration, rootability and soil erosion. Macroaggregate stability is known to respond rapidly to changes in soil management (Tisdall and Oades 1982). Six years after treatments were imposed, a significantly greater

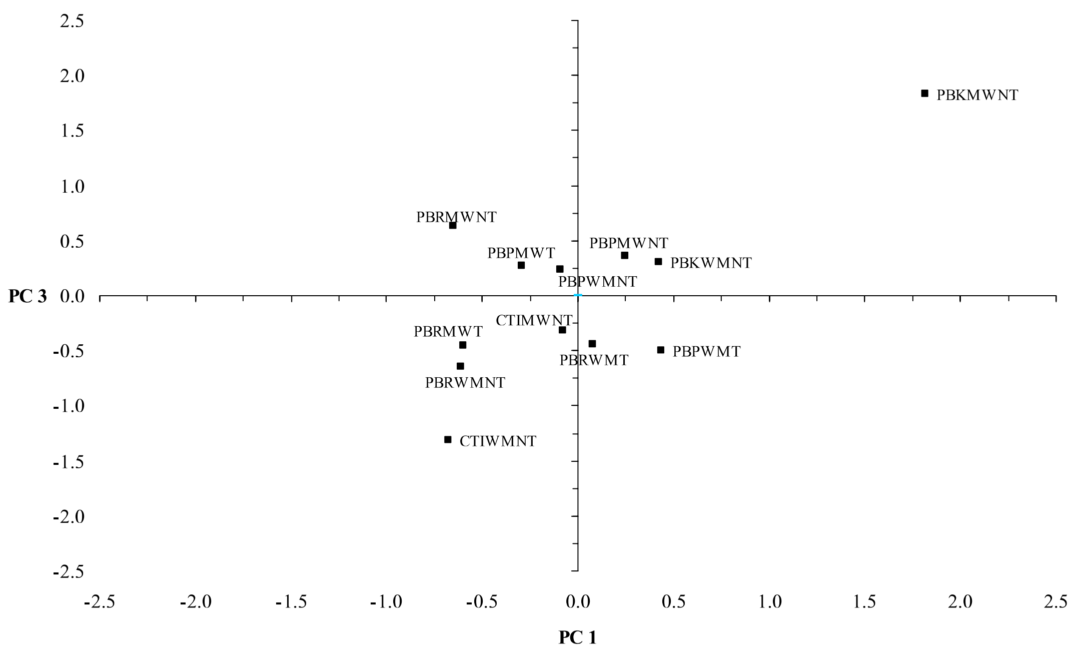

Fig. 3 Biplot of principal component 1 and 3 of the principal component analysis of all soil parameters with *M* maize; *W* wheat; *CB* conventionally tilled beds; *PB* permanent beds; *K* residue is fully kept in the field; *P* residue is partially kept in the field and partially removed; *R* residue is removed from the field; *T* with tied ridges; *NT* no tied ridges

amount of large and small macroaggregates was observed in the permanent raised beds with full residue retention compared to conventionally tilled raised beds, while significantly more free microaggregates were found in the conventional system (Table 2). Similar results were obtained by Wright and Hons (2004) comparing conventional tillage with zero tillage. Reduced aggregation in the conventional system is a direct and indirect result of the physical disturbance of soil structure (Beare et al. 1994; Six et al. 1998). The direct effect of tillage is due to the immediate breakdown of soil aggregates by the plow implements. Indirectly, the residue lying on the soil surface of the permanent raised beds protects the soil from raindrop impact. No protection is present in conventionally tilled raised beds, which increases susceptibility to further disruption (Six et al. 2000). The use of permanent raised beds with full residue retention increased the amount of large and small macroaggregates compared to residue removal in the same tillage system. This is in line with the results of CIMMYT's long-term tillage sustainability trial, where zero tillage without residue resulted in a loss of macroaggregate stability as opposed to the same tillage practice with residue retention (Govaerts et al. 2006). De Gryze et al. (2005) also reported an increased amount of large macroaggregates with increasing amounts of residue added. Fresh organic material creates hot spots of microbial activity where new soil aggregates are developed (Guggenberger et al. 1999; De Gryze et al. 2005).

The proportion of large macroaggregates is the most important fraction to evaluate the effect of management practices on soil aggregation, because it exerts a strong influence on the MWD, a comprehensive index for evaluating soil aggregation (Jiao et al. 2006). We observed that permanent raised beds with full residue retention significantly improved soil aggregation compared to conventionally tilled raised beds with residue incorporated. This indicates that not residue input alone is important to maintain good aggregation, but the combination of residue and reduced tillage. The difference among permanent bed treatments was evident from the greater degree of soil aggregation for permanent raised beds with full and partial retention of residue compared to residue removal. Loss of soil organic matter through extraction of crop residues facilitates the aggregate breakdown processes, as higher organic matter content in the surface reduces slaking and disintegration of aggregates when they are wetted (Blevins et al. 1998).

Wheat had significantly more large macroaggregates compared to maize. Plant roots are important binding agents at the scale of macroaggregates (Thomas et al. 1993; Six et al. 2004). The direct effect of roots on aggregation is greatest with perennial grass species due to the enmeshment of their extensive fine root systems with soil. Annual crops have smaller root systems and therefore a less positive direct effect on aggregation (Tisdall and Oades 1982). Wheat has a more horizontal growing root system as compared to maize and the plant population of wheat is higher resulting in a denser superficial root network. This denser root network could positively influence aggregate formation and stabilization (Six et al. 2004; Denef and Six 2005). Also, soil microbial biomass and bacterial diversity can influence aggregate formation (Six et al. 2004). Lupwayi et al. (1998, 1999) also found that in the wheat phase of different cropping rotations on a gray Luvisol in northern Alberta, soil microbial biomass and bacterial diversity were higher in reduced tillage systems compared to conventional tillage. Govaerts et al. (2007c) reported on the positive effect of wheat compared to maize on soil biological properties, and found that a wheat crop induced higher microbial populations and activity compared to maize for the central Highlands of Mexico.

Aggregate breakdown is a good measure for soil erodibility, as breakdown to finer, more transportable particles and microaggregates, increases erosion risk (Le Bissonnais 2003). Consequently, conventionally tilled raised beds and permanent raised beds without residue cover will have a greater erosion risk. Erosion is a mayor limiting factor of the target area (Sayre et al. 2001) and therefore the use of these production systems would not be recommendable.

C and N contents of the different soil size fractions

There is an effect of crop on the amount of C and N in free microaggregates that may be due to the input of crop residues with different characteristics, as well as the crop rhizosphere (Table 3). We found that microaggregates contained more total C and N when wheat was the last crop compared to maize as last crop. When residues are removed after harvest, wheat roots contribute to a reasonable amount of biomass while maize roots leaves less biomass. The addition or retention of plant residues in agricultural soils is a means to sustain soil organic matter content and thereby to enhance the biological activity, improve physical properties and increase the availability of nutrients (Hadas et al. 2004) as was also observed in this study (Table 3). Most comparative field studies have shown that no-tillage results in greater accumulation of soil organic matter in surface layers (0–20 cm) than does conventional tillage (Lal 1989; Kern and Johnson 1993). However, in other studies no significant differences have been reported where soil organic matter was measured throughout the entire profile (0–60 cm), under continuous cultivation with maize and spring cereal rotations (Angers et al. 1997) or over the top 0–100 cm, for soil cultivated with winter wheat and soybean (Sisti et al. 2004).

Carbon and nitrogen contents in microaggregates within the macroaggregates

Recent studies have revealed that the fraction of microaggregates occluded in the macroaggregates can serve as an indicator for C sequestration in agro-ecosystems, in particular in zero tillage systems (Denef et al. 2004). Similarly, enhanced C sequestration through C stabilization within the microaggregates within the macroaggregates has been confirmed in afforested (Six et al. 2002b; Del Galdo et al. 2003) and forested soils (Six et al. 2002b) compared to agricultural soils. In this study, significant differences were found between the management systems in C and N distribution across the separated size fractions. These differences were most pronounced between different tillage systems. The primary evidence that aggregate structure physically protects organic matter from microbial decomposition is provided by studies in which aggregates are crushed or ground. Carbon and N mineralization rates increased when the aggregate structure was disrupted. This was attributed in these studies to the exposure of organic matter, which was previously inaccessible to microbial attack (Oades 1984; Elliott and Coleman 1988). A similar process occurs during tillage in the field. Because the organic matter binding microaggregates together is generally assumed to be recalcitrant and in smaller pores that cannot be accessed by microorganisms, it is expected that organic matter associated with microaggregates will decompose more slowly than those associated with macroaggregates. Although the input of crop residues was similar in conventionally tilled raised beds with full residue retention and permanent raised beds with full residue retention (Sayre et al. 2005), the amount of C in the microaggregates differed. Tillage will change the macroaggregate turnover and Six et al. (1998, 1999) suggested that increased macroaggregate turnover under conventional tillage is a primary mechanism causing a decrease of soil C. In the conceptual model proposed by Six et al. (1998, 1999), the increase in macroaggregate turnover induced by tillage yields fewer new microaggregates within the macroaggregates and subsequently new free microaggregates compared to no tillage. Skjemstad et al. (1990) found that the incorporation of new C into free microaggregates is an important factor contributing to C-sequestration since C contained in free microaggregates has a slower turnover than C in macroaggregates (Jastrow et al. 1996).

Also, in the permanent bed planting system, significantly higher amounts of C were observed when residue was fully retained compared to partial retention and removal of residue. This indicates that nor tillage system alone, neither the input of crop residue increases stabilization of C, but the combination of both. The increased amount of C in the microaggregates in permanent raised beds with residue retention suggests this management practice will support increased C-sequestration in the soil. Conventional tillage is a system that will rather induce increased respiration of C.

The observed difference in C in the microaggregates within the macroaggregates of the soils of the different management practices of this study was not accompanied by a difference in the proportion of water-stable microaggregates within the macroaggregates. This was also found in other studies: Six et al. 2002b; Del Galdo et al. 2003; Denef et al. 2004. Denef et al. 2007. The original conceptual idea of a tight relationship between amount of microaggregates within the macroaggregates and C stabilization within the microaggregates within the macroaggregates as influenced by management (Six et al. 2000) is not applicable for all soil types and/or management systems (Denef et al. 2007). Enhanced C stabilization within the microaggregate within macroaggregate fraction under permanent raised beds compared to conventionally tilled raised beds was therefore related to the dynamic 'behaviour' rather than the 'amount' of the microaggregates (and the macroaggregates that protect them). In other words, similar to the conceptualized importance of both amount and turnover of macroaggregates for C sequestration upon reduced physical disturbance (Six et al. 1999), the differences in C concentration within the fraction of microaggregates occluded in the macroaggregates among management systems can be linked to differences in amount and stability as well as turnover of the microaggregates within macroaggregates (Denef et al. 2007). The macroaggregate-occluded-microaggregates have a slower turnover in permanent raised beds due to the protective environment within the macroaggregates. This slower turnover allows greater protection of cPOM and greater stabilization of mineral-bound C decomposition products in the macroaggregate-occluded-microaggregates (Denef et al. 2007).

$\delta\ ^{13}$C signature of aggregate size classes and particulate organic matter fractions

The $\delta\ ^{13}$C values of all soil fractions ranged from −17.43‰ to −21.96‰, which is typical of C derived from a rotational maize-wheat production system (Table 5). Details on the method and interpretation of the data can be found in: Cerri et al. (1985); Deleens et al. (1974); Balesdent et al. (1987). Many studies have used the ^{13}C natural abundance technique to generate quantitative information on long-term soil organic matter dynamics in temperate and tropical regions. The removal of residue resulted in larger negative $\delta\ ^{13}$C of the macro-, microaggregates and microaggregates within the macroaggregates compared to full retention of residue when maize was the last cultivated crop. More negative values indicate less dilution of the original C3 based $\delta\ ^{13}$C by the new input of C4 organic material in this wheat (C3), maize (C4) based rotation, due to the lack of input of fresh material as opposed to the full residue retention treatments and to a lesser extent of the partial residue retention treatments.

Principal component analysis

All wheat and maize treatments and their interactions with the different aggregation parameters are presented in Figs. 2 and 3. Treatments were clustered along the *X*- and *Y*-axes according to tillage practice and residue management. This indicated that tillage, residue management, and their interactions influence aggregation and C allocation. As would be expected, macroaggregates and the MWD were grouped together in the same PC. The proportion of large macroaggregates exerts a strong influence on the MWD (Jiao et al. 2006). Conventional raised beds with full residue retention were separated from all treatments, showing high values of intermediate PC1 and high PC2 values. The same residue input with permanent raised beds resulted in high PC1 and PC2 values. This indicates that input of fresh material resulted in younger soil organic fractions (high PC2), and a combination of zero tillage and residue retention resulted in increased macroaggregation. For permanent raised beds management practices were positioned along the *X*-axis based on residue retention, indicating a reduction in macroaggregate structure as residues were removed. PC3 grouped C and N content of the microaggregates within macroaggregates together. This confirms the close link between the C and N cycling found in most research (e.g. Schlesinger 1997). In general, increased retention of residue with permanent raised beds resulted in increased C and N in the microaggregates within macroaggregates. Conventionally tilled raised beds with all residue retained was grouped together with permanent raised beds with partial or no residue retention. This indicates that conventional tillage results in accelerated respiration of the input of the organic material, and thus in less stabilization of C within the microaggregates within the macroaggregates. Wheat as last crop resulted in higher values on PC3 compared to the same treatment with maize as last crop. This highlights again the positive effect of wheat crop roots on aggregation as discussed above.

In general, no effect of tied ridges was observed on the different soil parameters. However, tied ridges will help to keep water in the field, which otherwise would be lost as run off. In rain fed agriculture, raised permanent raised beds with tied ridges included at regular intervals across furrows between crops, help to hold rainfall and have been shown to improve water use efficiency in sorghum (Jones and Clark 1987) and corn (Harris and Krishna 1989; McFarland et al. 1991).

Conclusions

Permanent raised bed planting with retention of crop residue results in more stable macroaggregates and as such a reduced erosion potential, as well as an increased protection of C and N in the microaggregates within the macroaggregates, as compared to conventionally tilled raised beds. However, the positive effect of permanent raised beds is lost when all residues are removed. But, perhaps more important, permanent raised beds with partial residue retention for both crops provided acceptable levels of aggregate stability and C and N accumulation. Retaining only 30–50% of the organic residue still improved the soil structure considerably compared to plots where it was removed completely. Permanent raised beds without residue retention, however, is a practice leading to soil degradation.

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References

Angers DA, Bolinder MA, Carter MR, Gregorich EG, Drury CF, Liang BC, Voroney RP, Simard RR, Donald RG, Beyaert RP, Martel J (1997) Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Tillage Res 41:191–201

Azooz RH, Arshad MA (1996) Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Can J Soil Sci 76:143–152

Balesdent J, Mariotti A, Guillet B (1987) Natural 13C abundance as a tracer for studies of soil organic matter dynamics. Soil Biol Biochem 19:25–30

Beare MH, Hendrix PF, Coleman DC (1994) Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. Soil Sci Soc Am J 58:777–786

Blevins RL, Lal R, Doran JW, Langdale GW, Frye WW (1998) Conservation tillage for erosion control and soil quality. In: Pierce FJ, Frye WW (eds) Advances in soil and water conservation. Ann Arbor Press, MI, USA, pp 51–68

Bossuyt H, Six J, Hendrix PF (2002) Aggregate-protected carbon in no-tillage and conventional tillage agroecosystems using carbon-14 labeled plant residue. Soil Sci Soc Am J 66:1965–1973

Bruce RR, Langdale GW, Dillard AL (1990) Tillage and crop effects on characteristics of a sandy surface soil. Soil Sci Soc Am J 54:1744–1747

Cattell RB (1966) The scree test for number factors. Multivar Behav Res 1:245–276

Cerri C, Feller C, Balesdent J, Victoria R, Plenecassagne A (1985) Application du traçage isotopique naturel en 13C a l'étude de la dynamique de la matière organique dans les sols. C R Acad Sci Paris 300:423–428

De Gryze S, Six J, Brits C, Merckx R (2005) A quantification of short-term macroaggregate dynamics: influences of wheat residue input and texture. Soil Biol Biochem 37:55–66

Deen W, Kataki PK (2003) Carbon sequestration in a long-term conventional versus conservation tillage experiment. Soil Till Res 74:143–150

Del Galdo I, Six J, Peressotti A, Cotrufo MF (2003) Assessing the impact of land-use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable isotopes. Global Change Biol 9:1204–1213

Deleens E, Lerman JC, Nato A, Moyse A (1974) Carbon isotope discrimination by carboxylating reactions in C3, C4 and CAM plants. In: Avron M (ed) Proceedings of the third International Congress on Photosynthesis. Elsevier, Amsterdam, pp 1267–1276

Denef K, Six J (2005) Clay mineralogy determines the importance of biological versus abiotic processes for macroaggregate formation and stabilization. Euro J Soil Sci 56:469–479

Denef K, Six J, Paustian K, Merckx R (2001) Importance of macroaggregate dynamics in controlling soil carbon stabilization: short-term effects of physical disturbance induced by dry-wet cycles. Soil Biol Biochem 33:2145–2153

Denef K, Six J, Merckx R, Paustian K (2004) Carbon sequestration in microaggregates of no-tillage soils with different clay mineralogy. Soil Sci Soc Am J 68:1935–1944

Denef K, Zotarellia L, Boddey RM, Six J (2007) Microaggregate-associated carbon as a diagnostic fraction for management-induced changes in soil organic carbon in two Oxisols. Soil Biol Biochem 39:1165–1172

Elliott ET (1986) Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci Soc Am J 50:627–633

Elliott ET, Coleman DC (1988) Let the soil work for us. Ecol Bull 39:23–32

Emerson WW (1959) The structure of soil crumbs. J Soil Sci 10:235–244

Govaerts B, Sayre KD, Deckers J (2006) A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. Soil Till Res 87:163–174

Govaerts B, Barrera-Franco MG, Limón-Ortega A, Muñoz-Jiménez P, Sayre KD, Deckers J (2007a) Clasificación y evaluación edafológicas de tres sitios experimentales en el altiplano central de México. Tropicultura, In press

Govaerts B, Sayre KD, Lichter K, Dendooven L, Deckers J (2007b) Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rain fed maize/wheat systems. Plant Soil 291:39–54

Govaerts B, Mezzalama M, Unno Y, Sayre KD, Luna-Guido M, Vanherck K, Dendooven L, Deckers J (2007c) Influence of

tillage, residue management, and crop rotation on soil microbial biomass, and catabolic diversity. Appl Soil Ecol 37:18–30
Guggenberger G, Elliott ET, Frey SD, Six J, Paustian K (1999) Microbial contributions to the aggregation of a cultivated grassland soil amended with starch. Soil Biol Biochem 31:407–419
Hadas A, Kautsky L, Goek M, Kara EE (2004) Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover. Soil Biol Biochem 36:255–266
Harris BL, Krishna JH (1989) Furrow diking to conserve moisture. J Soil Water Conserv 44:271–273
IUSS Working Group WRB (2006) World reference base for soil resources. FAO, Rome, Italy, p 128
Jastrow JD, Boutton TW, Miller RM (1996) Carbon dynamics of aggregate-associated organic matter estimated by carbon-13 natural abundance. Soil Sci Soc Am J 60:801–807
Jiao Y, Whalen JK, Hendershot WH (2006) No-tillage and manure applications increase aggregation and improve nutrient retention in a sandy-loam soil. Geoderma 134:24–33
Jones OR, Clark RN (1987) Effects of furrow dikes on water conservation and dryland crop yields. Soil Sci Soc Am J 51:1307–1314
Kaiser HF (1960) The application of electronic computers to factor analysis. Educ Psychol Meas 29:141–151
Karlen DL, Varvel GE, Bullock DG, Cruse RM (1994) Crop rotations for the 21st-century. Adv Agron 53:1–45
Kemper WD, Chepil WS (1965) Size distribution of aggregates. In: Black CA (ed) Methods of soil analysis: Part I. Agronomy series no. 9. ASA, Madison, WI, USA, pp 499–509
Kern JS, Johnson MG (1993) Conservation tillage impacts on national and atmospheric carbon levels. Soil Sci Soc Am J 57:200–210
Ladd JN, Parsons JW, Amato M (1977) Distribution of immobilized nitrogen amongst soil fractions of different particle size and density. Soil Biol Biochem 9:309–318
Lal R (1989) Conservation tillage for sustainable agriculture: tropics vs. temperate environments. Adv Agron 42:85–197
Le Bissonnais Y (2003) Aggregate breakdown mechanisms and erodibility. In: Lal R (ed) Encyclopedia of soil science. Marcel Dekker, New York
Limon-Ortega A, Sayre KD, Francis CA (2000) Wheat and maize yields in response to straw management and nitrogen under a bed planting system. Agronomy J 92:295–302
Limon-Ortega A, Sayre KD, Drijber RA, Francis CA (2002) Soil attributes in a furrow-irrigated bed planting system in northwest Mexico. Soil Tillage Res 63:123–132
Lupwayi NZ, Rice WA, Clayton GW (1998) Soil microbial diversity and community structure under wheat as influenced by tillage and crop rotation. Soil Biol Biochem 30:1733–1741
Lupwayi NZ, Rice WA, Clayton GW (1999) Soil microbial biomass and carbon dioxide flux under wheat as influenced by tillage and crop rotation. Can J Soil Sci 79:273–280
McFarland ML, Hons FM, Saladino VA (1991) Effects of furrow diking and tillage on corn grain-yield and nitrogen accumulation. Agron J 83:382–386
Oades JM (1984) Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil 76:319–337
Paustian K, Collins HP, Paul EA (1997) Management controls on soil carbon. In: Paul EA, Paustian K, Elliot ET, Cole CV (eds) Soil organic matter in temperate agroecosystems: long-term experiments in North America. CRC Press, Boca Raton, FL, pp 15–49
SAS Institute (1994) SAS User's Guide. SAS Inst., Cary, NC, USA
Sayre KD (2004) Raised-bed cultivation. In: Lal R (ed) Encyclopedia of soil science. Marcel Dekker, New York
Sayre KD, Mezzalama M, Martinez M (2001) Tillage, crop rotation and crop residue management effects on maize and wheat production for rain fed conditions in the altiplano of central Mexico. In Garcia-Torres L, Benites J, Martinez-Vilela A (eds) Conservation agriculture, a worldwide challenge. Proceedings of the I World Congress on Conservation Agriculture, Madrid, 1–5 October 2001. XUL, Cordoba, Spain. pp. 575–585
Sayre KD, Limon-Ortega A, Govaerts B (2005) Experiences with permanent bed planting systems CIMMYT, Mexico. In Roth CH, Fisher RA, Meisner CA (eds) Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico. Proceedings of a workshop held in Griffith, NSW, Australia; March 1 to 3, 2005. ACIAR Proceedings No. 121, pp. 12–25
Schlesinger WH (1997) Biogeochemistry: an analysis of global change. 2nd edition ed. Academic, San Diego, CA
Sena MM, Frighetto RTS, Valarini OJ, Tokeshi H, Poppi RJ (2002) Discrimination of management effects on soil parameters by using principal component analysis: a multivariate analysis case study. Soil Tillage Res 67:171–181
Sisti CPJ, dos Santos HP, Kohhann R, Alves BJR, Urquiaga S, Boddey RM (2004) Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Tillage Res 76:39–58
Six J, Elliott ET, Paustian K, Doran JW (1998) Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci Soc Am J 62:1367–1377
Six J, Elliott ET, Paustian K (1999) Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci Soc Am J 63:1350–1358
Six J, Elliott ET, Paustian K (2000) Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under zero tillage agriculture. Soil Biol Biochem 32:2099–2103
Six J, Conant RT, Paul EA, Paustian K (2002a) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241:155–176
Six J, Callewaert P, Lenders S, De Gryze S, Morris SJ, Gregorich EG, Paul EA, Paustian K (2002b) Measuring and understanding carbon storage in afforested soils by physical fractionation. Soil Sci Soc Am J 66:1981–1987
Six J, Bossuyt H, De Gryze S, Denef K (2004) A history of research on the link between (micro)aggregates, soil biota,

and soil organic matter dynamics. Soil Tillage Res 79: 7–31

Skjemstad JO, Lefeuvre RP, Prebble RE (1990) Turnover of soil organic-matter under pasture as determined by c-13 natural abundance. Aust J Soil Res 28:267–276

Soil Survey Staff (1998) Keys to soil taxonomy. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC, USA

Thomas RS, Franson RL, Bethelenfalvay GJ (1993) Separation of vesicular–arbuscular mycorrhizal fungus and root effects on soil aggregation. Soil Sci Soc Am J 57:77–81

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates. J Soil Sci 33:141–163

Wright AL, Hons FM (2004) Soil aggregation and carbon and nitrogen storage under soybean cropping sequences. Soil Sci Soc Am J 68:507–513