Carbon Sequestration and Soil Aggregation in Center-Pivot Irrigated and Dryland Cultivated Farming Systems

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Although irrigation is considered a beneficiary management for increasing soil organic C (SOC) stocks in (semi)arid environments, our understanding of the impact of irrigation on soil organic matter (SOM) dynamics in the field remains limited. We investigated the effect of irrigation on soil C storage in relation to soil aggregation by measuring C stocks of bulk soil and different aggregate fractions in the top 20-cm layer of center-pivot irrigated vs. dryland farming systems in semiarid southwestern Nebraska. The irrigated fields (IRR) showed increased C inputs and larger SOC stocks than the dryland cultivated fields (DRY). Fractionation of bulk soil samples into non-microaggregate-associated particulate organic matter (free POM) and microaggregate-associated POM, silt, and clay fractions indicated that the larger bulk SOC stock under IRR was explained solely by an increase in microaggregate-associated C storage Wet sieving of bulk soil showed that microaggregation was remarkably low under DRY and did not increase under IRR, suggesting that the protection of microaggregates inside macroaggregates was no prerequisite for C sequestration under IRR. The results of this study confirm the potential of irrigation to increase soil C stocks through preferential sequestration of C inside microaggregates, but question our understanding of the mechanisms underlying this preferential sequestration.

Abbreviations: cPOM, coarse particulate organic matter (>250 µm); DRY, dryland cultivated treatment; iPOM, intramicroaggregate particulate organic matter; IRR, center-pivot irrigated treatment; mClay, microaggregate-associated clay fraction; micro-C, microaggregate-associated C; mSilt, microaggregate-associated silt fraction; NV, native vegetation; POM, particulate organic matter; SOC, soil organic carbon; SOM, soil organic matter; TOC, total organic carbon.

Increasing the amount of C sequestered in cropland through improved agricultural management has become an important part of the strategy to mitigate CO_2 emissions to the atmosphere (Lal et al., 1998; Intergovernmental Panel on Climate Change, 2001). Examples of management practices that enhance soil C stocks are reduced tillage and increasing cropping intensity (Paustian et al., 2000), but also irrigation is believed to be a potential beneficial management for increasing soil C stocks (Follett, 2001). Carbon sequestration rates through irrigation have been estimated to reach as high as 50 to 150 kg ha^{-1} yr^{-1} (Lal et al., 1998). These estimates, however, are based solely on increased C inputs due to enhanced biomass production on irrigation. Yet, irrigation can affect the soil C balance in several other ways as well. For example, irrigation can greatly stimulate microbial activity in regions suffering from drought. In a study of Churchman and Tate (1986), irrigation led to a decrease of C stocks in soils under pasture, suggesting that its effect on microbial activity and SOM decomposition was potentially more dominant than its effect on C input.

Besides increasing C input and microbial activity, irrigation can also affect soil structure. Many studies have reported a negative impact of irrigation on physical properties such as bulk density, porosity, and hydraulic conductivity (Moreno et al., 1986; Elnaim et al., 1987; Poznyak, 1990; Al-Nabulsi, 2001),

as well as severe seal and crust formation due to the impact of water drops (Shainberg et al., 1997). In irrigated arid regions, irrigation water is often highly sodic and could induce a high exchangeable sodium proportion on the soil complex, which increases dispersion of clay particles, leading to degradation of soil structure (Amezketa, 1999) and decreased macroaggregate resistance to drop impact (Levy and Torrento, 1995). Finally, the different soil moisture regime resulting from irrigation can also affect soil structure by reducing the occurrence of dry–wet cycles. Although dry–wet cycles in aggregated soils have been shown to have detrimental effects on aggregation (e.g., Utomo and Dexter, 1982), the overall impact of dry–wet cycles on soil structure depends on several soil factors (Six et al., 2004) and appears to be only short term (Denef et al., 2001).

By its effect on soil structure, irrigation can influence the C balance of the soil. It is well known that there exists a feedback mechanism between aggregation and SOM dynamics (for an extensive review on this topic, see Six et al., 2004). Increased SOM input (e.g., as a result of irrigation) can lead to increased aggregate formation (De Gryze et al., 2005; Kong et al., 2005), which in turn enhances C sequestration by physical protection of SOM inside aggregates. Disruption of aggregates by irrigation water, however, could have the opposite effect. Recent studies on aggregate–SOM relationships in agricultural systems have indicated the importance of the macroaggregate-occluded microaggregate fraction for stabilizing C under more sustainable agricultural management systems like no-tillage (Six et al., 2000; Denef et al., 2004) or on increased residue return to the soil (Kong et al., 2005). These studies suggested that the macroaggregate-occluded microaggregate-associated C fraction may be a highly accurate and general diagnostic fraction for changes in total SOC in response to changes in tillage and, potentially, other management practices. Examination of the C stabilization capacity of this fraction under irrigation management can help elucidate mechanisms of C sequestration in irrigated systems.

The aim of this work was (i) to compare SOC storage and aggregation in center-pivot irrigated and dryland farming systems in the western Nebraskan Great Plains, (ii) to investigate if a link between C input, SOC storage, and aggregation can be found in these agricultural systems, and (iii) to determine which physical fractions are responsible for any observed SOC differences between irrigated and dryland managed systems. We hypothesized that: (i) SOC and macroaggregation levels are higher under center-pivot irrigated than dryland cultivated management; and (ii) the difference in total SOC stocks between irrigated and dryland treatments is reflected in a difference in macroaggregate-occluded microaggregate-associated C.

MATERIALS AND METHODS
Site and Treatment Description

Sampling was done in May and November 2004 on two farms near Imperial, southwestern Nebraska (40°31′ N, 101°38′ W, 1029 m above sea level). The mean annual temperature is 11°C. Annual precipitation averages 570 mm. The sampling sites have a flat topography and cover three soil series: Alliance (fine-silty, mixed, superactive, mesic Aridic Argiustoll), Goshen (fine-silty, mixed, superactive, mesic Pachic Argiustoll), and Rosebud (fine-loamy, mixed, superactive, mesic Calcidic Argiustoll).

The four fields that were sampled had been under a dryland winter wheat (*Triticum aestivum* L.)–summer fallow (WF) rotation from 1940 until around 1970, when a similar center-pivot irrigation system

with drop sprinklers was established at both farms. On each field, this system consisted of an irrigated circular area (pivot) of about 50 ha (approximately 800-m diameter, see Fig. 1). Since the fields were squares with sides of the same length as the pivot diameter, the four corners of each field (each about 3.5 ha; Fig. 1) did not receive irrigation water and stayed under the dryland WF system. For the irrigated pivots, the dominant cropping system was continuous corn (*Zea mays* L.), which occasionally changed into a WF rotation. Since 2000, all fields have been managed under conservation (chisel) tillage with a crop rotation of corn (extra disking tillage), winter wheat, and soybean [*Glycine max* (L.) Merr.] for the irrigated pivots, and a WF–corn rotation for the dryland corners. Within the pivots, a first irrigation event generally takes place in May to incorporate herbicides into the soil (approximately 19 mm). The true irrigation season usually starts at the end of June and continues until the end of August. During these months, up to 60 mm wk^{-1} can be applied in dry periods. Most farmers in this area initiate an irrigation event when soil moisture is depleted to 50% of the available water capacity, to keep the root zone below field capacity in case rainfall is received. Crop yield data were provided by the farmers for the last 4 yr. From these yield data, average annual total (below- + aboveground) residue C inputs per treatment were estimated (S. Williams, Natural Resource Ecology Lab., personal communication, 2005), which can be found in Table 1.

The differentiation of each field in 1970 into irrigated- and dryland-managed parts formed the basis for our irrigated vs. dryland treatment comparison. The pivot zones of each field are referred to as the IRR treatment, while the dryland corner zones are referred to as the DRY treatment. A native grassland area adjacent to one of the fields and about half the size of the fields (NV treatment) was included as a reference; before cultivation, all sites were under similar native grassland vegetation. Relative locations of all fields and treatments can be seen in Fig. 1.

Sampling Design

To address the spatial variability inevitably linked with the large size of the fields, a specific sampling design was used (Fig. 1, enlarged field). On each field, the pivot zone was divided into four quadrants,
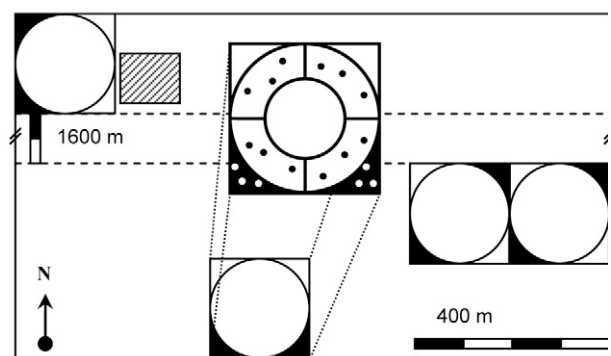
Fig. 1. Map of sampled fields with scheme of the soil sampling design. The locations of the four sampled fields are shown as squares, showing the irrigated pivot area (white circles) and randomly selected dryland corners (black areas) inside each field. One field is enlarged to show the sampling design of the pivot area. Each pivot was divided into four quadrants; the inner half of the pivot was excluded to avoid boundary effects. Three samples were randomly taken inside each quadrant and inside each selected corner (dots). In the native vegetation area (rectangle with diagonal lines), six random sample locations were chosen.

and two of the field's four dryland corners were randomly selected. In each quadrant and selected corner, three sample locations were randomly selected; the inner half of the pivot area was avoided to exclude boundary effects. For the native grassland area, six random locations were selected.

At each sample location, three soil cores (5.5-cm diameter) were taken approximately 1 m apart using a hydraulic Giddings probe. Each core was divided into two depths: 0 to 5 and 5 to 20 cm. The soil from the three cores was combined per depth, bagged, and transported to the laboratory with minimal compaction. Once in the laboratory, field-moist samples were passed through an 8-mm sieve by gently breaking up the soil clods along their natural planes of failure, and subsequently air dried. Organic material >8 mm was removed during sieving. For

each sample, bulk density was calculated based on gravimetric water content and sampling core volume, particle size distributions were determined, and total organic C content measured. Since sampled locations were homogeneous with respect to texture and the spatial variability of C contents was low within each pivot or corner (data not shown), the three air-dried soil samples from each quadrant or corner were mixed per depth to reduce the extensive fractionation work. For IRR, 16 composited samples were obtained per depth (four fields × four quadrants), while DRY had eight samples per depth (four fields × two corners). Similarly, the native grassland samples were mixed pairwise in a random manner, resulting in three (pseudo)replicates per depth for NV. All published results are from the composited samples.
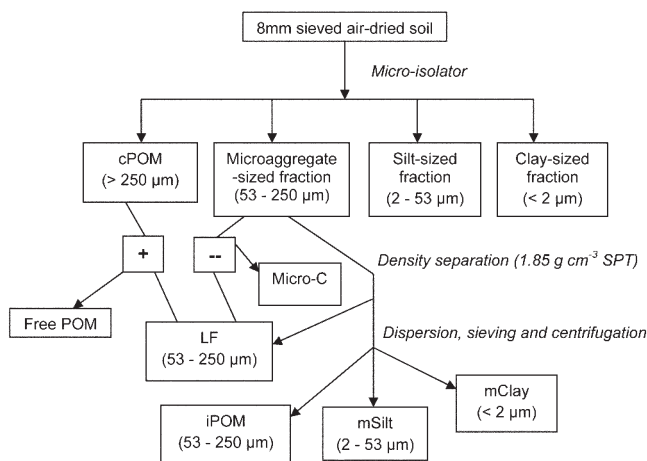
Aggregate Separation

Aggregate size distribution was determined by a wet sieving technique, adopted from Elliott (1986). Briefly, a 100-g air-dried soil sample was submerged in deionized water for 5 min and subsequently sieved on a 250-µm sieve by manually moving the sieve 50 times up and down in the water in 2 min. The fraction that remained on the sieve (macroaggregate fraction, >250 µm) was backwashed into an aluminum pan, oven dried overnight at 60°C, and weighed the next day. The soil suspension that passed the sieve was poured onto a 53-µm sieve and sieving was repeated. Both the fraction remaining on the sieve (microaggregate fraction, 53–250 µm) as well as the material <53 µm (silt- + clay-sized fractions) were transferred into separate aluminum pans, oven dried, and weighed the next day. Sand contained in a specific aggregate size class was not considered to be part of those aggregates and therefore a sand correction was performed by subtracting the weight of sand from the total weight of each size class:

$$\text{sand-corrected aggregate}\,(\%\,\text{w/w}) =$$
$$\left(\frac{\text{size-class weight - sand weight of same size-class}}{\sum_{\text{all fractions}} \text{sand-corrected weights}} \right) 100 \qquad [1]$$

To do this, the weight of macroaggregate- and microaggregate-sized sand was determined by complete dispersion of a subsample of the macroaggregate or microaggregate size fraction, respectively, in 5% sodium hexametaphosphate solution, followed by sieving on a 250- or 53-µm sieve, respectively.

Microaggregate Isolation and Fractionation of Associated Organic Matter

Due to the lack of significant amounts of macroaggregates in the cultivated treatments, macroaggregate-occluded microaggregates could not be isolated for C analyses. Instead, C distribution was only investigated among fractions <250 µm. Therefore, a new fractionation sequence was used (Fig. 2). In a first fractionation step, 8-mm-sieved soil was disrupted in water by a "microisolator" shaking device (for a

Fig. 2. Fractionation scheme used to study C stocks in different soil organic matter fractions (Micro-C = total microaggregate-associated fraction; cPOM = coarse particulate organic matter >250 µm; LF = light-fraction particulate organic matter not occluded inside microaggregates; Free POM = sum of cPOM and LF, i.e., non-microaggregate-associated particulate organic matter; iPOM = intramicroaggregate POM; mSilt and mClay = microaggregate-associated silt and clay fractions, respectively).

detailed description of the device, see Six et al., 2000). Although this device is generally used to isolate microaggregates out of macroaggregates, we used bulk soil instead of macroaggregates to isolate *total* water-stable microaggregates (i.e., free as well as macroaggregate-occluded). The following four fractions were obtained: coarse intermicroaggregate particulate organic matter (cPOM, >250 μm), microaggregate-sized fraction (53–250 μm), silt-sized fraction (2–53 μm), and clay-sized fraction (<2 μm). The soil suspensions of all fractions were transferred to aluminum pans, oven dried overnight at 60°C, and weighed the next day. For the microaggregate-sized fraction, sand correction was performed with the weight of the intramicroaggregate particulate organic matter (iPOM) + sand fraction (see below) using Eq. [1].

Second, microaggregates were separated from particulate organic matter (POM) that was located outside the microaggregates (light fraction, LF) by density fractionation of the microaggregate-sized fraction, following the method of Six et al. (1998). Briefly, a 6-g subsample of the microaggregate-sized fraction was suspended in 45 mL of sodium poly-tungstate (1.85 g cm^{-3}), gently mixed, and centrifuged at 20°C for 60 min (1250 g). The floating light material (LF) was aspirated onto a 20-μm nylon filter and collected. The heavy fraction (microaggregates) that remained after density fractionation was further fractionated into iPOM + sand and microaggregate-derived silt and clay (mSilt and mClay, respectively) by adding glass beads to the suspension and shaking on a reciprocal shaker for 18 h. Next, the suspension was poured over a 53-μm sieve, and the fraction remaining on the sieve (iPOM + sand) was retained. The soil material that went through the sieve was collected in plastic bottles and centrifuged to separate the mSilt and mClay fractions. All collected fractions were transferred to aluminum pans and oven dried at 60°C.

Carbon and Nitrogen Analyses

Total C and N concentrations of bulk soil samples and the cPOM, microaggregate-, silt-, and clay-sized fractions, iPOM, and mSilt and mClay fractions were measured with a LECO CHN-1000 analyzer (LECO Corp., St. Joseph, MI). Carbon and N concentrations of the LF were measured on a Carlo-Erba NA 1500 CN analyzer (Carlo-Erba, Milan, Italy) coupled to a Micromass VG isochrom-EA mass spectrometer (Manchester, UK) because of small sample sizes. Inorganic C concentrations of bulk samples were determined by measuring the pressure increase due to evolved CO_2 on hydrolysis of the carbonates in a 1 M HCl solution (Sherrod et al., 2002). Organic C (OC) was then calculated by difference. For those samples that contained inorganic C in the bulk sample, inorganic C concentrations were determined for all fractions as well. Due to small sample sizes, the mSilt and mClay fractions of those samples that contained inorganic C were fumigated with HCl to remove carbonates (Harris et al., 2001) before measuring them on the mass spectrometer. In this way, a direct value for the OC was obtained. Total organic C (TOC) stocks were expressed on a total soil basis (g OC m^{-2}) by multiplying each sample's OC concentration in kilograms OC per kilogram of soil with the bulk density of that sample and the appropriate depth interval. The OC stocks of the different fractions were calculated similarly, after multiplying the fraction's OC concentration by the weight proportion of that fraction. The C stock of the free POM, i.e., organic matter that is located outside of and therefore not protected inside microaggregates, was calculated as the sum of C stocks of the cPOM and LF fractions. To obtain the amount of C that was protected inside the microaggregates (micro-C), the amount of C in the LF fraction was subtracted from the amount of C in the microaggregate-sized fraction.

Moisture Content Modeling

To obtain a general trend of differences in soil moisture regime between IRR and DRY, the BUDGET soil water and salt balance model (Raes, 2002) was used to simulate the soil moisture content in the 0- to 5- and 5- to 20-cm layers during the growing season of corn under irrigated and dryland conditions. Data on the local climate, soil texture, crop characteristics, and irrigation scheduling were used as inputs. Irrigation events were simulated during July and August by applying 19 mm of water whenever soil moisture content dropped below 50% of the readily available water content. This scheme agrees with the irrigation scheme used by the farmers at the site. Default parameters available in the model for a loam soil were used as inputs for volumetric moisture content at saturation (46%), field capacity (31%), and the permanent wilting point (15%).

Statistical Analyses

Data were analyzed as an unbalanced two factorial design using the SAS statistical package for mixed models ANOVA-MIXED (SAS Institute, 2003), with irrigation treatment as the main factor. Since the NV treatment was a separate nonreplicated area instead of an extra treatment per field, this treatment could not be included in the statistical design. Therefore, statistical analyses were only performed with IRR and DRY treatments, and comparisons with NV were only made when obvious differences were present. To take into account natural field variability, the replicate fields (n = 4) were treated as a random variable. In this way, the analyzed fields are seen as samples taken out of a population of fields rather than as exact replicates. Separation of treatment means was tested with the Tukey–Kramer test for unbalanced designs. A significance level of P < 0.05 was used.

RESULTS
Bulk Soil Characteristics

While surface layer bulk density of the cultivated treatments (1.24 g cm^{-3} for IRR and 1.21 g cm^{-3} for DRY) was higher than that of NV (1.10 g cm^{-3}), no differences in bulk density were observed between IRR and DRY at any depth (Table 2). Textural analysis showed no significant differences in sand, silt, or clay content between IRR and DRY in either the 0- to 5- or 5- to 20-cm layers, and all treatments had loam textures. The TOC stocks decreased in the order NV > IRR > DRY for both depths (Table 2). For the whole 0- to 20-cm layer, IRR had a significantly higher TOC stock than DRY, but the TOC stock under IRR stayed well below the NV TOC stock. Total N stocks followed the same trends as those found for TOC stocks (Table 2). Estimations of residue C input with yield-conversion formulas based on 4-yr averaged crop yields showed that residue C input for IRR was almost 2.5 times as high as for DRY, and 1.5 times as high as for NV (Table 1).

Aggregation

At both depths, macroaggregation was very low (around 10% of the soil weight) in both IRR and DRY compared with NV (up to 60%) (Fig. 3). In the 0- to 5-cm layer, IRR had a significant but small positive effect on macroaggregation. The amount of microaggregates in the surface layer obtained by wet sieving was greatest under IRR and decreased as follows: IRR > DRY > NV. Concomitant with the larger amounts of macro- and microaggregates in IRR vs. DRY in the 0- to 5-cm layer, the <53-μm fraction was smaller under IRR than DRY. At the 5- to 20-cm depth, no differences were found between IRR and DRY for any of the three size fractions.

The weight of the total microaggregate fraction that was obtained by microaggregate isolation (and thus comprised of

Table 2. Bulk density, total organic carbon (TOC) stocks, total nitrogen (TN) stocks, and particle size distribution in the 0- to 5-, 5- to 20-, and 0- to 20-cm depths under native vegetation (NV), center-pivot irrigation (IRR), and dryland cultivation (DRY).

| Depth	Treatment	Bulk density	TOC	TN	Sand	Silt	Clay
cm		g cm^{-3}	———g m^{-2}———		———— g kg^{-1} soil————		
	NV	1.10 (0.04)†	1500 (81)	142 (10)	460 (40)	380 (20)	160 (20)
0–5	IRR	1.24 (0.02) a	940 (51) a	98 (5) a	460 (30) a	340 (40) a	200 (10) a
	DRY	1.21 (0.03) a	746 (62) b	79 (6) b	460 (30) a	350 (40) a	190 (10) a
	NV	1.41 (0.04)	2474 (114)	283 (13)	510 (50)	330 (30)	170 (20)
5–20	IRR	1.44 (0.02) a	2348 (50) a	262 (5) a	440 (30) a	330 (40) a	220 (10) a
	DRY	1.47 (0.03) a	1917 (62) b	228 (6) b	440 (30) a	330 (40) a	230 (10) a
	NV	1.33 (0.04)	3974 (188)	425 (23)			
0–20	IRR	1.39 (0.02) a	3301 (88) a	360 (8) a			
	DRY	1.41 (0.02) a	2664 (106) b	307 (10) b			

† Values in parentheses are standard errors of the mean (n = 16 for IRR, n = 8 for DRY, and n = 3 for NV). Values followed by different lowercase letters statistically differ between IRR and DRY treatments and within depth.

free as well as macroaggregate-occluded microaggregates) is given in Fig. 4a. In the surface layer, IRR had significantly more microaggregates than DRY: approximately 60% of the total soil weight of IRR was made up of microaggregates, while this was only 45% for the DRY treatment. In the 5- to 20-cm layer, all treatments had similar amounts of total microaggregates.

Free and Microaggregate-Associated Carbon Distribution

At both depths, micro-C concentrations differed among treatments as follows: NV > IRR > DRY (Fig. 4b) and were

higher in the 0- top 5-cm than the 5- to 20-cm layer for all treatments. On a total-soil basis (g C m^{-2}), both IRR and DRY had comparable amounts of C in the free POM fraction at both depths (Fig. 5). This amount was less than half of that in the free POM fraction of NV. For the micro-C fraction, however, a significantly higher C stock was observed for IRR than DRY, with the difference between IRR and NV being less pronounced. No significant differences were found among all treatments for the C stocks of the silt and clay fractions (silt and clay in Fig. 5).
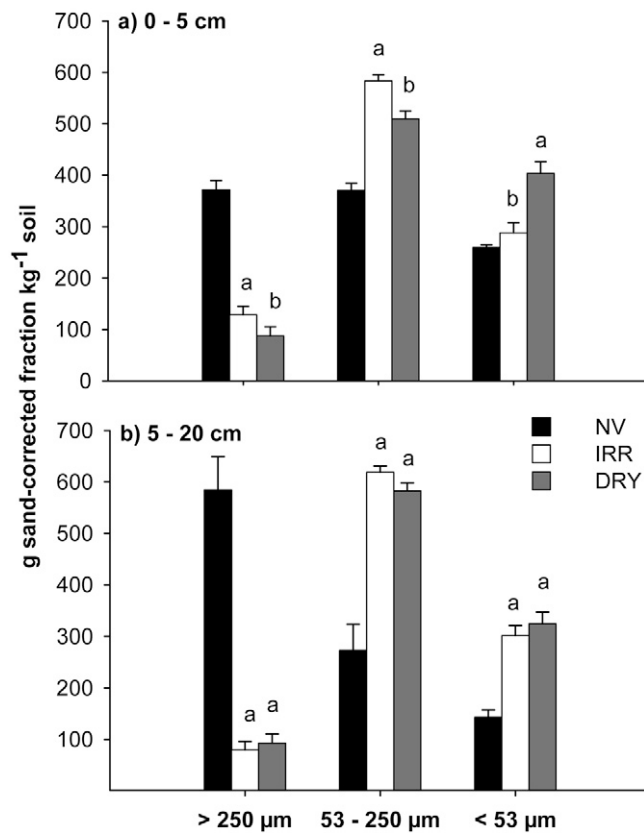
Fig. 3. Aggregate size distribution as determined by wet sieving for (a) the 0- to 5-cm and (b) the 5- to 20-cm layers of soils under three management treatments (NV = native vegetation; IRR = center-pivot irrigated; DRY = dryland cultivated). Error bars represent standard errors. Values followed by different lowercase letters statistically differ between IRR and DRY and within depth.
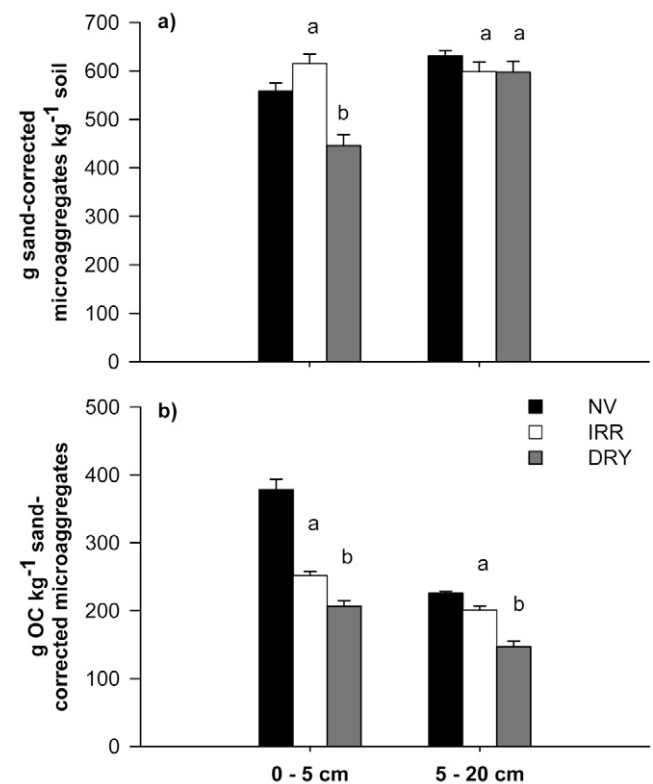
Fig. 4. (a) Amount of total microaggregates obtained by microaggregate isolation and (b) microaggregate-associated organic C (OC) concentration isolated from bulk soil samples from the 0- to 5- and 5- to 20-cm soil layers under three management treatments (NV = native vegetation; IRR = center-pivot irrigated; DRY = dryland cultivated). Error bars represent standard errors. Values followed by different lowercase letters statistically differ between IRR and DRY and within depth.

Intramicroaggregate Carbon Distribution

Since the greatest difference in C stocks between IRR and DRY was found in the micro-C fraction (Fig. 5), it was decided to look at the distribution of C among different micro-aggregate-associated fractions. The distribution of micro-C among these fractions is shown in Fig. 6. In all treatments and depths, mClay C stock contributed the most to the total micro-C stock. For the 0- to 5-cm layer, a significant increase in mClay C was observed under IRR compared with DRY, but this difference was absent at deeper depth. The iPOM C stocks were significantly higher under IRR than under DRY at both depths. For the mSilt C, the same trends were found as for iPOM C, although the difference in the 0- to 5-cm layer was not significant.

Modeled Soil Moisture Content

Figure 7 shows the evolution of soil moisture content in the 0- to 5- and 5- to 20-cm layers during the corn growing season, as modeled with BUDGET (Raes, 2002). Under dryland conditions and at the 0- to 5-cm depth, large variations in soil moisture occurred in relatively small time intervals (Fig. 7a). Under irrigated conditions, these variations strongly decreased (Fig. 7b), and soil moisture was almost always above field capacity. Although less pronounced, the same trends were visible in the 5- to 20-cm layer.
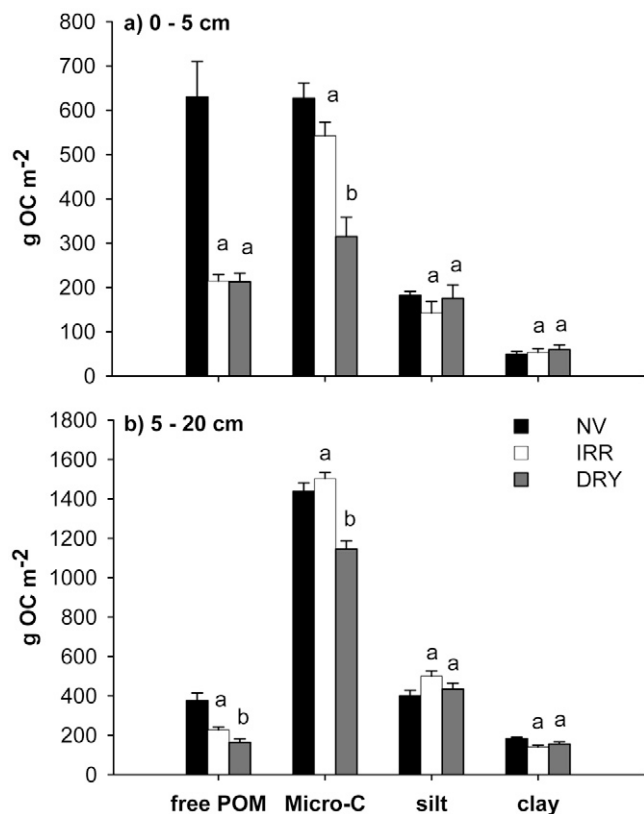
Fig. 5. Organic C (OC) stocks of non-microaggregate-associated particulate organic matter (free POM), microaggregate-associated C (Micro-C), and silt and clay fractions for (a) the 0- to 5-cm and (b) 5- to 20-cm layers of soils under three management treatments (NV = native vegetation; IRR = center-pivot irrigated; DRY = dryland cultivated). Error bars represent standard errors. Values followed by different lowercase letters statistically differ between IRR and DRY and within depth.

DISCUSSION

Carbon Stocks and Aggregation

Our first aim was to compare C stocks and aggregation between irrigated and dryland managed treatments. Carbon storage under irrigation was clearly higher than under dryland management, since C stocks in the top 20 cm of the soil were almost 25% higher under IRR than under DRY (3301 g m^{-2} for IRR vs. 2664 g m^{-2} for DRY). This higher C storage could be linked to a greater C input under irrigation, since estimated crop residue C inputs under IRR were 2.5 times as high as those under DRY; however, calculations of turnover times of bulk soil C based on C input estimates and measured C stocks—assuming steady state of the system—showed that the turnover time of C under IRR was only 50% of that under NV and DRY. This indicates a faster cycling of C through the soil under IRR than DRY, most likely because irrigation favors microbial activity by offsetting moisture limits on decomposition, which are typical for these dry areas. These results show that the C sequestration potential of irrigation cannot be evaluated in terms of a C input effect alone (e.g., Lal et al., 1998). Changes in soil C dynamics caused by irrigation have to be included as well.
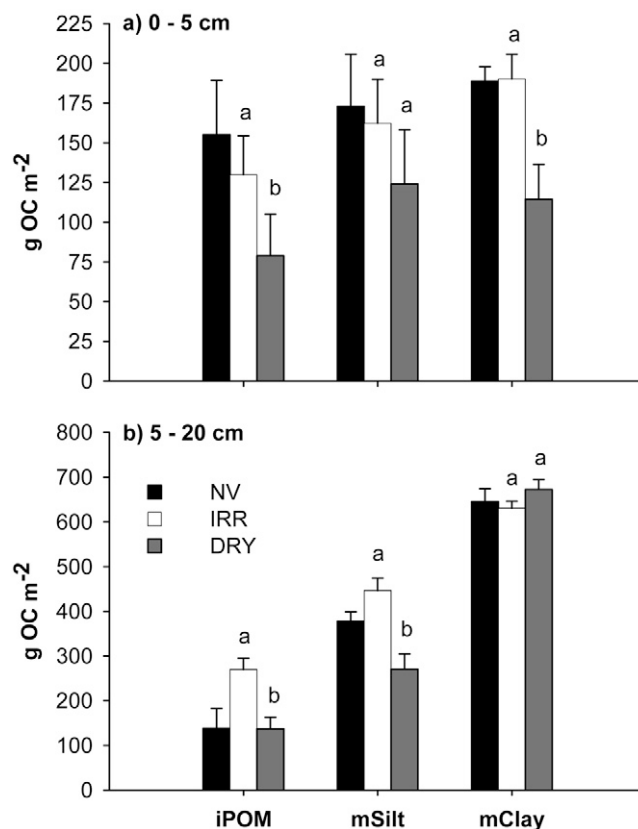
Fig. 6. Organic C (OC) stocks of intramicroaggregate fractions (iPOM = intramicroaggregate POM; mSilt = microaggregate-associated silt; mClay = microaggregate-associated clay) for (a) the 0- to 5-cm and (b) 5- to 20-cm soil layers under three management treatments (NV = native vegetation; IRR = center-pivot irrigated; DRY = dryland cultivated). Error bars represent standard errors. Values followed by different lowercase letters statistically differ between IRR and DRY and within depth.

Since C data from right before the start of irrigation were not available, it was not possible to calculate an accurate C sequestration rate for the irrigated fields. Before the installment of the center-pivot irrigation system, however, the IRR and DRY fields had the same cropping and management history, consisting of 30 yr of dryland agriculture. Therefore, if we assume that the soil C content was at an equilibrium state at the start of irrigation and did not change under DRY since then, we can estimate the C sequestration rate under irrigation based on the measured 2004 soil C contents of IRR and DRY fields. Under this assumption, an average C accumulation rate of 19 g m^{-2} yr^{-1} (637 g C m^{-2} over 33 yr) was calculated for the 0- to 20-cm layer under irrigation. This estimate is slightly higher than the range estimated by Lal et al. (1998), which was 5 to 15 g C m^{-2} yr^{-1}.

The percentage of soil present as macroaggregates was much lower in DRY than in NV. Cultivation is known to result in a decrease of macroaggregation due to physical disturbance from tillage operations (Tisdall and Oades, 1982). Furthermore, a reduced C input and increased microbial decomposition—due to increased aeration—of SOM on dryland cultivation of native grassland soils can further explain the diminished macroaggregation in dryland

Fig. 7. Modeled soil moisture regime in the 0- to 5- and 5- to 20-cm soil layers during the growing season (May–October) of corn (a) under dryland and (b) under irrigated treatments. The BUDGET software package for modeling the soil water balance (Raes, 2002) was used. Irrigation events were simulated during July and August by applying 19 mm of water whenever soil moisture content dropped below 50% of the readily available water content. This scheme agrees with the irrigation scheme used by the farmers at the site. Saturation = 46%, field capacity = 31%, and permanent wilting point = 15% (default BUDGET parameters for a loam soil).

cultivated soils relative to native soils (Elliott, 1986). In contrast to what we hypothesized, irrigation caused only a minor increase in macroaggregation compared with DRY, and remained unexpectedly low. There were several reasons why we predicted an increase in macroaggregation under irrigation. First, increased residue-C additions have been found to induce increases in macroaggregates (De Gryze et al., 2005). Second, stimulation of microbial activity can lead to increased macroaggregate formation due to the production of aggregate binding agents (Tisdall and Oades, 1982). Thus by increasing residue C inputs and by making the soil moisture regime more favorable for microbial activity, IRR was expected to show more macroaggregates than DRY. Interestingly, much higher macroaggregate levels were found in the NV treatment, indicating the potential of this particular soil type in this specific climatic environment (similar for all treatments) to form large amounts of stable macroaggregates. We therefore postulate that other factors than climate and inherent soil properties were responsible for the low macroaggregate levels under IRR.

One factor could be the time of sampling, since we did not sample the fields throughout the year. It might be possible that average macroaggregation during the year was higher than the value found at the time of sampling. Half of the fields were sampled right after tillage (April–May 2004), however, while the other half was sampled right after harvest (November 2004), with no significant effect of sampling time found on macroaggregation (data not shown). Thus, even after a full growing and irrigation season, macroaggregation had not increased under IRR relative to DRY, although more samplings throughout the year are necessary to verify this assumption. The low amount of macroaggregates under IRR suggests that the hypothesized positive effect of irrigation on aggregation could not counteract the negative effect of physical disturbance by tillage practices (similar for IRR and DRY). In addition, root growth, stimulation of microbial activity, and reduced dry–wet cycles during the irrigated crop growing season (see Fig. 7) did not promote aggregation. This could have been due to an increase in exchangeable sodium percentage (ESP) under IRR. Levy and Torrento (1995) tested the influence of exchangeable Na on the resistance of macroaggregates to drop impact. They found that macroaggregate stability decreased 25% when ESP increased from 0.3 to 1.3%. We observed a similar increase in ESP in IRR compared with DRY (from 0.49 to 0.99% and from 0.45 to 1.41% in the 0–5- and 5–20-cm layers, respectively). A final factor possibly contributing to the lack of macroaggregation in IRR could be a negative effect of the high moisture content on fungal growth. Fungal hyphae are seen as major contributors to macroaggregate formation (Tisdall and Oades, 1982). Since fungi have been reported to suffer more rapidly from O$_2$ depletion than bacteria (Frey et al., 1999), the high moisture content under irrigation could have favored bacterial growth over fungal growth.

Microaggregates: Preferential Carbon Sequestration Sites under Irrigation

Our second aim was to identify the physical fraction(s) responsible for increased C storage under irrigation. Although several studies have demonstrated the importance of the macroaggregate-occluded microaggregate fraction for long-term C stabilization under improved agricultural management (e.g., Denef et al., 2004; Kong et al., 2005), this fraction did not seem to play a major role in C sequestration under irrigation since only 10% of the soil mass

was found in the macroaggregate fraction. Therefore, the role of "total" microaggregates as preferential C sequestration sites under IRR management was investigated.

Comparison of the C distribution among free and microaggregate-associated C fractions showed that 88% of the difference in total C between IRR and DRY was accounted for by the difference in micro-C. Free POM, on the other hand, accounted for only 10% of the total C difference between these two treatments, while silt and clay fractions were not affected by irrigation at all. These results indicate that increased C storage under irrigation occurs through preferential C stabilization inside microaggregates. The increase in micro-C was due to not only an increased amount of microaggregates (Fig. 4a) but also an increase in their C concentration (Fig. 4b) (the former only in the 0–5-cm layer). The distribution of C inside microaggregates (Fig. 6) shows that this increase was the result of both increased iPOM C and increased mSilt and mClay C (the latter two depending on the depth).

Comparison of NV with DRY showed a different trend than comparison of IRR with DRY. Free POM and micro-C each accounted for about half of the total C difference between NV and DRY, with silt and clay fractions again showing no difference between treatments. This major decline of free-POM C when soils under native vegetation are brought into dryland cultivation has been reported by several other researchers as well (Six et al., 1998; Cambardella and Elliott, 1992; Tisdall and Oades, 1982). The lower C storage in the micro-C fraction under DRY, however, suggests that microaggregates can be more vulnerable to disturbance through cultivation than sometimes assumed (Tisdall and Oades, 1982). This again stresses the importance of microaggregates in determining the effects of land-use management on C storage.

Link between Aggregation and Carbon Dynamics under Irrigation

The results of our study agree with studies dealing with identifying the importance of the microaggregate fraction as a preferential C stabilization site in alternative management systems (Six et al., 2000; Del Galdo et al., 2003; Denef et al., 2004; Kong et al., 2005). The microaggregate fraction investigated in these studies was always occluded in the macroaggregate fraction, however. Our findings are surprising, therefore, since they contradict and question the necessity of a protective environment provided by macroaggregates for preferential C sequestration by microaggregates, as postulated by Six et al. (2000). The macroaggregate-occluded microaggregate fraction can apparently only play a role in C stabilization (i) in soils that have the inherent capacity to form macroaggregates and (ii) under management systems that improve macroaggregate levels (e.g., Kong et al., 2005) or slow down macroaggregate turnover (e.g., Six et al., 2000). In our study, the increased C inputs under irrigation were not able to improve macroaggregate levels, possibly due to intensive tillage. In a center-pivot farming system in Otis, CO, similar to ours but under no-tillage, a significant increase in macroaggregation was observed under irrigation compared with dryland management (Denef, unpublished data, 2006). This supports the idea of disruption by tillage having a greater impact on aggregate levels than increased residue inputs under irrigation. Possibly, irrigation

management combined with no-tillage could form an even better C sequestration management option than irrigation alone, due to the possible additional protection and stabilization of SOM in macroaggregate-occluded microaggregates.

It appeared impossible to confirm with our study that occlusion into macroaggregates was the mechanism by which C sequestration in microaggregates occurred under irrigation. Therefore, another explanation is needed to explain the mechanism behind C sequestration under irrigation. Although it is not possible to elucidate such a mechanism with the present work, we do believe key issues involved are (i) a high substrate availability due to increased residue inputs and (ii) a more favorable moisture regime for microbial activity under irrigation. Since free POM mainly consists of plant residues (Christensen, 2001), this fraction should be the first to increase with increased residue inputs. Although residue C inputs under IRR were 2.5 times as high as under DRY, there was no accumulation of free POM under IRR compared with DRY. This indicates that the higher moisture content under IRR promotes residue degradation by microbes to a much larger extent than under DRY. The rather vigorous formation of microbial exudates would then lead to an increased formation of microaggregates from silt and clay particles bonded together with microbes and small POM particles, giving them an increased C content and stability compared with microaggregates under dryland management. This is supported by the distribution of C inside microaggregates (showing an increase in both iPOM C and mSilt or mClay C under IRR). Additionally, we postulate that the high moisture content under IRR contributed to the stabilization of micro-C by increasing the extent of anaerobic zones inside the aggregates (Elliott and Coleman, 1988). More research is needed to verify if moisture content and residue C input indeed determine the potential of C sequestration under irrigation.

CONCLUSIONS

The results of this study showed that C storage under center-pivot irrigation was 25% higher than under dryland cultivation in an agricultural system in southwestern Nebraska. This greater C storage was mostly attributed to higher C sequestration inside microaggregates, but without the need for a protective environment of water-stable macroaggregates. Therefore, we postulate that the macroaggregate-occluded microaggregate fraction is only important for C sequestration in those management systems that can improve macroaggregate levels or slow down macroaggregate turnover, which was not the case for our study. Instead, we formulated a concept that attributed the increased C stabilization in free microaggregates under irrigation to a pronounced increase in microbial activity due to high moisture content and increased residue inputs, resulting in formation of stable microaggregates consisting of physically protected iPOM encapsulated in a matrix of silt and clay particles bound by chemically protected microbial exudates.

This study confirms that irrigation management is a promising management option for enhancing soil C sequestration in (semi)arid agricultural areas such as southwestern Nebraska. Yet more studies on other irrigation systems under different management practices and across different climatic regions are needed to come to a more accurate image of the overall effects of irrigation on soil C stocks. Furthermore, the surprising results on the link between aggregation and C dynamics under irrigation stress the

need for further integrated process-level research on this topic, since a better understanding of the mechanisms governing the C balance under irrigation is a prerequisite for a general evaluation of irrigation management as a best management practice for soil C sequestration in agricultural soils of (semi)arid regions.

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