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Research article

Impact of direct sowing mulch-based cropping systems on soil carbon, soil erosion and maize yield

Eric SCOPEL[a]*, Antoine FINDELING[b], Enrique CHAVEZ GUERRA[c], Marc CORBEELS[a]

[a] System Mixed Research Unit, Centre de coopération Internationale en recherche Agronomique pour le Développement (CIRAD), avenue Agropolis, 34398 Montpellier Cedex, France
[b] Environmental risks of recycling Research Unit, Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), avenue Agropolis, 34398 Montpellier Cedex, France
[c] Natural Resources Group, International Centre for Maize and Wheat Improvement (CIMMYT), El Batan, Texcoco, Mexico

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Abstract – We studied the impact of direct seeding mulch-based cropping systems (DMC) on soil characteristics and maize production compared with conventional tillage management (CT) in the semi-arid region of western Mexico. Mulch treatments included 0, 1.5, 3 and 4.5 Mg ha^{-1} of added surface crop residues. The study was carried out from 1994 to 1998 on a Dystric Cambisol soil in La Tinaja in the state of Jalisco. Water runoff, soil erosion, soil C changes, maize aboveground biomass and grain yield were monitored on field plots. The results show that mulch treatments reduced annual water runoff losses by 10 to 50% relative to the conventional tillage treatment depending on residue amounts, slope and year. Soil erosion losses were reduced by 50 to 90%. Over a 5-year period soil carbon levels under mulch increased by 23 to 29% compared with conventional tillage, mainly due to increased crop residue inputs and reduced soil carbon erosion under mulch treatment. In the year with the most intense rainfall (1997), the conventional treatment lost about 800 kg of C ha^{-1} i.e. 2 to 7 times greater than mulch treatments. Maize grain yields were greater by 170 to 190% under mulch. Yield increases under mulch occurred each year, notably due to improved water and nutrient use efficiency. Potential yield benefits under mulch in the longer term due to build-up of soil organic matter and reduction of soil erosion were not obvious in our experiment. Overall, even small amounts of surface residue are effective at sustaining rainfed maize productivity under the semi-arid conditions of western Mexico. The short-term yield benefits are a promising factor for adoption of direct seeding mulch-based systems in the region.

direct sowing / mulch / runoff / erosion / soil organic carbon / Mexico

1. INTRODUCTION

In the dry regions of western Mexico annual rainfall varies between 400 and 800 mm. In spite of these low total amounts, rainfall can be very intense, causing substantial water runoff and soil erosion on cropped fields (Scopel et al., 2004). Maize, the staple food crop in Mexico, covers about 80% of the rainfed cropped area in the region. Continuous maize monocropping under conventional tillage with one crop per year is the common practice. As maize is fairly sensitive to water stress and highly demanding for nutrients, management of available water resources and soil fertility is crucial to ensure a sustainable productivity. Inappropriate management practices have led to serious grain yield losses in the region, both in the short term as a result of poor water use, and in the long term through decline of soil fertility (Scopel et al., 2001). Such a diagnosis is not site-specific and similar processes have been observed in other tropical regions (Lal, 1997). This is extremely harmful for smallholder farmers, who depend strongly on maize production for food and income. Therefore, alternative management systems that increase water use efficiency and protect soil resources are to be tested for sustained rainfed maize production in the drylands of western Mexico.

Direct seeding mulch-based cropping is a promising option of sustainable management in the tropics. It has the potential to increase crop water use efficiency and typically conserves soil resources (Lal, 1998). With direct seeding mulch-based cropping, tillage is no longer practiced and the soil is at all times covered by a mulch of crop residues.

The main beneficial effects of a crop residue mulch in reducing surface water runoff and soil erosion are well established (Alberts and Neibling, 1994). The mulch protects the topsoil from sealing and crusting, which enhances water infiltration (Findeling et al., 2003; Rao et al., 1998). Mulching also increases the soil surface roughness and reduces the runoff flow velocity (Gilley et al., 1987). Moreover, mulch particles reduce the kinetic energy of rainfall drops, decreasing "splash" effects with soil detachment and transport (Mannering and Meyer, 1963). All these effects become more important with higher amounts of crop residue and a larger proportion of the soil covered (Meyer et al., 1970). Furthermore, direct seeding mulch-based cropping systems enhance the build-up of soil organic matter, principally as a result of increased carbon inputs and decreased soil disturbance (Paustian et al., 1997). This is especially true under conditions that allow intensive direct seeding

* Corresponding author: eric.scopel@cirad.fr

mulch-based cropping systems with reduced fallow frequencies and a second harvest crop or a cover crop during the same growing season (Sá et al., 2001).

The amount of crop residue that is retained on the surface as a mulch depends on the residue availability, and hence on crop biomass production, and on the residue destinations. In the semi-arid region of Mexico, potential biomass production is rather low (6 to 10 Mg dry matter ha^{-1}), principally because of limited rainfall. Moreover, a large proportion of the crop residues are used as fodder for livestock during the 7- to 8-month-long dry season. As a result, crop residues available for mulching generally are limited and provide only partial cover of the soil (Scopel et al., 2001).

The objective of this study is to assess the impacts of direct seeding mulch-based cropping systems with varying levels of surface crop residues on water and soil conservation in the maize production systems of semi-arid western Mexico. We hypothesized that direct seeding mulch-based cropping systems with relatively small amounts of residues on the surface already represent improved management with great beneficial effects on water conservation and soil carbon storage. Therefore, we monitored water runoff and soil erosion and quantified soil carbon changes on experimental field plots under different tillage and residue management practices during the period from 1994 to 1998.

2. MATERIALS AND METHODS

2.1. Study site

The study was conducted in La Tinaja (19°42'N, 103°47'W, 1200 m altitude) in the state of Jalisco, Mexico on a sandy-clayey soil (Dystric Cambisol with 15% clay, 25% loam and 61% sand) that is representative of the region. The climate is semi-arid tropical with a mean temperature during the growing season of about 25 °C. Mean annual rainfall in La Tinaja is 525 mm with 80 to 90% of the rain occurring between June and September. Dry spells of 10 days or longer are, however, common during the rainy season. Rainfall events generally occur at the end of the day and have high intensities that may sometimes reach 50 mm h^{-1}or more.

2.2. Experiments

We installed three experiments (experiments A, B and C) on the middle slope of a toposequence that covers an area of about 8000 m^2 in a farmer's field. The distance between adjacent experiments was less than 50 m. The soil was the same over the whole experimental area, whereas the slope of the three experimental sites ranged from 3 to 7%.

For experiment A, a series of six runoff plots corresponding to six tillage and crop residue management treatments was established in 1995 on a field with a slope of 7%. Each plot measured 20 m^2 (2 m × 10 m) and was enclosed by stainless steel sheets of 20 cm height that were inserted to a soil depth of 10 cm. The plots were installed in the direction of the slope with an outlet system for collecting runoff water and eroded solid matter. The six treatments were: (1) bare soil that was neither tilled nor sown (BS), (2) maize directly sown with no tillage and without a mulch of crop residues (DS-0), (3) maize directly sown into a residue mulch of 1.5 Mg dry weight ha^{-1} (DMC-1.5), (4) maize directly sown into a residue mulch of 3 Mg ha^{-1} (DMC-3), (5) maize directly sown into a residue mulch of 4.5 Mg ha^{-1} (DMC-4.5), and (6) maize under conventional tillage with disc ploughing to a soil depth of 10 cm (CT). Tillage and sowing were done parallel to the contour. The mulch in the DMC treatments consisted of maize harvest residues from the previous cropping year. The different treatments were realized by redistributing the harvest residue material at the start of the rainy season. Residues were completely removed in the treatments with no mulch. Water runoff and soil erosion data were collected from 1995 to 1997.

A second series of runoff plots (experiment B) was established in 1997 on an adjacent site with a homogeneous slope of 3%. Individual plot sizes and setup were the same as in Experiment A, but with only 4 treatments: DS-0, DMC-1.5, DMC-4.5 and CT. Water runoff and soil erosion data were collected in 1997.

In both experiments A and B, surface water runoff was determined after each rainfall event or sequence of events by measuring the volume of water collected in a series of containers (each of 1.2 m^3) at the outlet of each plot. The runoff amount was referred to the plot area in order to calculate runoff depth (mm). Annual runoff and the annual average runoff coefficient, defined as the annual average ratio of runoff depth over rainfall per rainfall event, were calculated for each treatment. The amount of eroded solid material was estimated by taking a subsample of 1 liter from the runoff suspension in the containers after it had been thoroughly stirred (and after removing any vegetal residues that had fallen into the containers). The subsamples were filtered through a 1 μm paper filter to retain the solid particles. The mass of solid material was determined gravimetrically after oven drying at 105 °C for 24 hours and referred to the plot area. Annual soil losses (Mg ha^{-1} $year^{-1}$) and sediment concentrations of the runoff flows (kg soil ha^{-1} mm^{-1} runoff) were calculated for each treatment. A Student's paired t-test was used to evaluate treatment differences for both water runoff coefficients and sediment concentrations in runoff flow.

In experiment C, treatments DS-0, DMC-1.5, DMC-4.5 and CT were applied in a randomized complete block design with two replicates to evaluate the effects of tillage and residue management on maize yield and soil organic matter. Each plot measured 600 m^2 and their slopes ranged from 5 to 7%. The experiment was conducted over 5 growing seasons (1994 to 1998). Each year a maize crop was grown that was sown in early July and harvested in late November. At harvest final grain yield and total aboveground dry matter were determined. Before the start of the rainy season (March–April) crop harvest residues were redistributed according to the amounts of mulch in each treatment. In September 1998 soil samples were collected from the 0 to 2.5, 2.5 to 5, 5 to 10 and 10 to 20 cm surface soil layers at 4 locations (replicates) in each plot. All soil samples were air-dried for several days and then manually crushed to pass through a 2-mm sieve. All visible plant material larger than 2 mm was removed. A subsample of 20 to 25 g from this 2-mm sieved soil was powder-ground to pass through a 300-m sieve using a stainless steel ball-mill grinder before analysis for

Table I. Main rainfall characteristics for 1995, 1996 and 1997 in La Tinaja, Mexico.

	Total Number of events	Total rainfall	Number of events > 5 mm	Total rainfall (> 5 mm)	Number of events > 40 mm	Total rainfall (> 40 mm)
1995	63	359 mm	25	299 mm	1	42 mm
1996	42	576 mm	27	525 mm	2	103 mm
1997	37	693 mm	34	667 mm	5	278 mm

organic carbon by dry combustion in a CHN elemental analyzer. For soil carbon stock calculations we used soil bulk density measurements from another sampling on the experimental site. Four replicate undisturbed soil samples were collected at each plot in 0–10, 10–20 and 20–30 cm layers by the core method using volumetric steel rings (500 cm^3). An analysis of variance was used to evaluate effects of tillage and harvest residue management on total aboveground biomass, grain yield and soil organic carbon concentrations. A Newman Keul's test was used to assess differences between treatment means at the 0.05 significance level.

3. RESULTS AND DISCUSSION

3.1. Rainfall

Rainfall characteristics of the years 1995, 1996 and 1997 are shown in Table I. In 1995 total annual rainfall was very low (359 mm). However, that year had the highest total number of rainfall events (63), but only 40% were with rainfall superior to 5 mm and only one event was with rainfall higher than 40 mm. In 1996 total annual rainfall (576 mm) was close to the annual mean for La Tinaja. Sixty percent of the events during that year were with rainfall between 5 and 40 mm, and 2 events were with rainfall higher than 40 mm. The year 1997 was the wettest year with a total annual rainfall of 693 mm. It was also a stormy year, since events with rainfall higher than 40 mm accounted for about 40% of the annual total.

3.2. Water runoff and soil erosion

Annual water runoff and average runoff coefficients from experiment A (on plots with a 7% slope) for 1995, 1996 and 1997 are, respectively, shown in Figure 1 and Table II. As expected, annual water runoff was correlated with rainfall: total runoff losses were greatest in the wettest year (342 mm of runoff in 1997), and least in the driest year (85 mm in 1995). The stormy character of the rainfall during 1997 was reflected in the annual average runoff coefficients, that were consistently higher for all tillage and residue treatments in 1997 (49% on average over all treatments) than in 1996 and 1995 (30 and 24%, respectively). These high runoff coefficients clearly demonstrate the high likelihood of runoff on cropped soils in the region. Residue and tillage treatment effects were consistent over the 3 years. In treatments without surface residues (BS, CT and DS-0) about 30% or more of the annual rainfall was lost through runoff on plots with a 7% slope (experiment A, Tab. II). Mulching with 1.5 Mg ha^{-1} of crop residues reduced annual water runoff by 28% (in 1997) to 57% (in 1995) compared with the DS-0 treatment (Fig. 1). As expected, larger

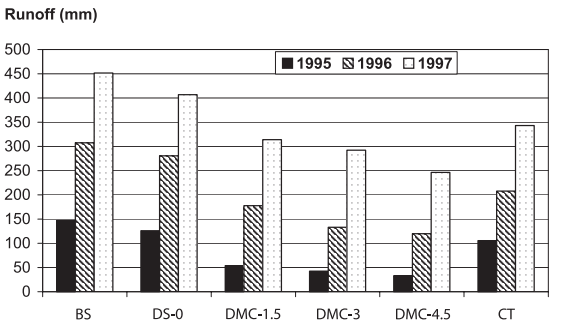

Figure 1. Effect of tillage and residue management treatments on total annual runoff on a 7% slope (experiment A) in La Tinaja, Mexico during 1995 (with 359 mm rainfall), 1996 (576 mm rainfall) and 1997 (693 mm rainfall). BS = bare soil control, DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-3 = direct sowing with 3 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.

amounts of mulch reduced runoff even more. With the retention of 4.5 Mg ha^{-1} of surface crop residues, runoff losses were reduced to 8, 17 and 28% of total rainfall, respectively, in 1995, 1996 and 1997 (Tab. II). The results also demonstrated that the effect of higher residue amounts became relatively less important in 1997, when rainfall was high with several stormy events (Fig. 1, Tab. II). Tillage (treatment CT) had a significant effect in reducing annual runoff compared with the treatment with no tillage and without surface residues (DS-0) in 1996 and 1997

Table II. Effect of tillage and residue management treatments on average runoff coefficients in La Tinaja, Mexico for experiments A and B.

	Tillage/residue treatments					
	BS[a]	DS-0	DMC-1.5	DMC-3	DMC-4.5	CT
Exp. A 1995	0.39a[b]	0.32b	0.14c	0.10d	0.08d	0.28b
Exp. A 1996	0.50a	0.45b	0.28c	0.19d	0.17d	0.31c
Exp. A 1997	0.58a	0.52a	0.43b	0.35c	0.28c	0.45b
Exp. B 1997	–[c]	0.27a	0.14b	–	0.06c	0.15b

[a] BS = bare soil control, DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-3 = direct sowing with 3 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.
[b] The treatments with the same letter do not display a significant difference between them using the Student's t-test at 5%.
[c] Not determined.

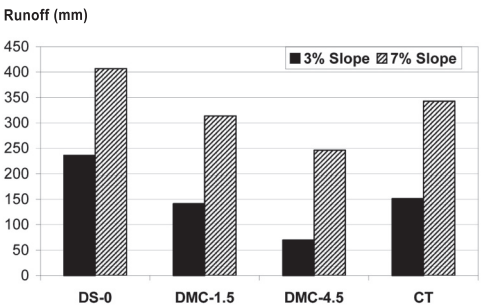

Figure 2. Effect of tillage and residue management treatments on total annual runoff on a 7% (experiment A) and 3% slope (experiment B) in La Tinaja, Mexico during 1997. DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.

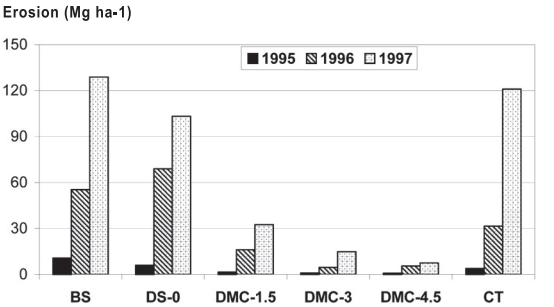

Figure 3. Effect of tillage and residue management treatments on total annual soil loss on a 7% slope (experiment A) in La Tinaja, Mexico during 1995 (with 359 mm rainfall), 1996 (576 mm rainfall) and 1997 (693 mm rainfall). BS = bare soil control, DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-3 = direct sowing with 3 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.

(Fig. 1, Tab. II). The tillage effect occurred mainly during the early rainfall events, but disappeared afterwards due to progressive soil slaking with successive rain events. On the contrary, surface residue treatment effects were remarkably consistent throughout the season (data not shown).

To evaluate the slope effect, runoff data collected during 1997 from experiment B on plots with a slope of 3% were compared with those of experiment A on a slope of 7% (Fig. 2). On average, runoff decreased by about 55% on plots with a 3% slope compared with a 7% slope. Treatment effects were still significant on the plots with a 3% slope: mulching reduced runoff by between 40% (under DMC-1.5) and 70% (under DMC-4.5), whereas tillage (CT) reduced runoff by about 35% compared with no-tillage (DS-0) (Fig. 2).

Table III shows mulch and tillage effects on annual average sediment concentrations in runoff water for the years 1995, 1996 and 1997. Overall, sediment concentrations were more than 6 times higher in 1997 than in 1995, illustrating the erosive character of the rain in 1997. The year 1996 was in-between with sediment concentrations that were about twice as high as those in 1995. Mulching significantly reduced sediment concentrations in runoff water compared with the BS and DS-0 treatments without mulch, with the strongest effects occurring with the largest amounts of surface residue (Tab. III). The treatment and year effects on runoff and sediment concentration were cumulated in the effects on soil erosion (Fig. 3). On average, soil losses were about 15 and 2.5 times higher in 1997 than in 1995 and 1996, respectively. The corresponding runoff losses were on average only 4 and 1.7 times higher in 1997 compared with 1995 and 1996, respectively. Mulching with 1.5 Mg ha^{-1} of crop residues significantly reduced soil losses by 76, 77 and 68% compared with the DS-0 treatment in 1995, 1996 and 1997, respectively. The effect became slightly more significant with a larger amount of crop residues, but the absence or presence of mulch was the overruling factor. As expected, annual soil losses were lower on the plots with a 3% slope (experiment B) compared with those on the plots with a 7% slope (experiment A). On the 3% slope plots erosion control was almost complete for the DMC treatments, especially when larger amounts of crop residues were retained (data not shown).

Table III. Effect of tillage and residue management treatments on average sediment concentration in the runoff water (kg ha^{-1} mm^{-1} runoff) in 1995, 1996 and 1997 on plots with a 7% slope (experiment A) in La Tinaja, Mexico.

Year	Tillage/residue treatments					
	BS[a]	DS-0	DMC-1.5	DMC-3	DMC-4.5	CT
1995	61.2a[b]	38.8ab	19.7c	20.8bc	16.7c	26.8abc
1996	127.2a	149.7a	49.1b	24.9b	24.6b	78.0ab
1997	302.1a	297.1ab	125.9cd	75.4d	105.9cd	277.0bc

[a] BS = bare soil control, DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-3 = direct sowing with 3 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.
[b] The treatments with the same letter do not display a significant difference between them using the Student's t-test at 5%.

These results clearly demonstrate the high efficiency of direct seeding mulch-based cropping systems at reducing water runoff and soil erosion in the semi-arid conditions of Mexico. This agrees with previous work on the effect of crop residue mulching on water and soil runoff losses (Lal, 1998; Mannering and Meyer, 1963). We showed that in this region direct seeding mulch-based cropping systems with small amounts of surface residues and a partial cover of soil surface (20% for DMC-1.5 and 40% for DMC-4.5) are still effective at controlling surface water flows. It has been found elsewhere (Findeling et al., 2003) that a partial crop residue mulch considerably delays runoff appearance and reduces runoff propagation. Small quantities of crop residues are sufficient to form protective barriers on the soil surface that hinder surface runoff. These barriers act as 'microdams' that make water flows more sinuous and, consequently, increase the potential for water to infiltrate into the soil (Gilley et al., 1991). Besides, the 'microdam' effect reduces the kinetic energy of water flows, which diminishes the solid transport by water (Gilley et al., 1987). It is also known that surface residues considerably dissipate raindrop energy and thereby decrease soil detachment (Mannering and Meyer, 1963). Previous studies indicate that surface crop residues efficiently protect the physical structure of topsoil and minimize surface

Table IV. Effect of tillage and residue management treatments on soil carbon concentration and bulk density in different soil layers (experiment C) in La Tinaja, Mexico in 1998.

	Tillage/residue treatments[a]			
	DS-0[b]	DMC-1.5	DMC-4.5	CT
C content (%)				
0–2.5 cm	0.79a[c]	1.26b	1.62c	0.65a
2.5–5 cm	0.77a	0.93b	1.01b	0.71a
5–10 cm	0.73a	0.76a	0.73a	0.71a
10–20 cm	0.64a	0.67a	0.62a	0.59a
Bulk density ($g\ dm^{-3}$)				
0–10 cm	1.41b	1.42b	1.45b	1.26a
10–20 cm	1.44a	1.48a	1.50a	1.42a
20–30 cm	1.33a	1.34a	1.34a	1.31a

[a] The treatments had been established each year from 1994 to 1998.
[b] DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.
[c] The treatments with the same letters do not display a significant difference between them using the Newman Keul's test at 5%.

Table V. Effect of tillage and residue management treatments during 5 cropping years (from 1994 to 1998) on soil carbon stocks in the 0–20 cm soil layer, in La Tinaja, Mexico.

	Tillage/residue treatments			
	DS-0[a]	DMC-1.5	DMC-4.5	CT
Total carbon (Mg ha^{-1})	19.7	23.1	24.5	17.1
Total carbon (Mg ha^{-1}) corrected for differences in Bulk Density	19.7	22.5	23.6	18.3
Absolute difference with DS-0 (Mg ha^{-1})	–	+2.8	+3.9	–1.4
Relative difference with DS-0 (%)	–	+14.2%	+19.8%	–7.1%

[a] DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.

sealing, thereby enhancing water infiltration into soil (Valentin and Bresson, 1992). In addition, the higher soil porosity at the soil surface that is observed under direct seeding mulch-based cropping as a result of increased soil organic matter content and macrofauna activity (Findeling et al., 2003) promotes water conductivity and sorptivity.

3.3. Soil carbon contents

After five cropping seasons significantly higher carbon concentrations in the 0–2.5 and 2.5–5 cm soil layers were observed under the DMC treatments compared with the treatments without residues (DS-0 and CT) (Tab. IV). However, no significant differences between treatments were observed at greater depths. Treatment effects on bulk density were only significant for the 0–10 cm soil layer. Not tilling the soil resulted in a significantly higher bulk density (on average 1.4 g dm^{-3} under no-tillage versus 1.26 g dm^{-3} under tillage). When expressed on a surface basis, substantial differences in soil carbon content of the 0–20 cm topsoil layer were observed after five years between treatments. Carbon contents under DMC-1.5 and DMC-4.5 were, respectively, about 14% and 20% higher compared with the DS-0 treatment (Tab. V). On the other hand, the carbon content under conventional tillage (CT) was 7% lower when compared with the direct seeding treatment with no mulch (DS-0) (Tab. V).

Table VI. Effect of tillage and residue management treatments on grain yield and total aboveground biomass of maize (Mg dry matter ha^{-1}) in La Tinaja, Mexico from 1994 to 1998 (experiment C).

	Tillage/residue treatments			
	DS-0[a]	DMC-1.5	DMC-4.5	CT
Grain yield				
1994	0.79bc[b]	1.17b	2.17a	0.42c
1995	1.57b	2.75a	3.22a	1.92b
1996	2.02c	4.16a	4.34a	3.12b
1997	0.36b	3.69a	4.17a	1.10b
1998	1.92c	3.37a	3.78a	2.56b
Total above ground biomass				
1994	2.78b	3.25b	5.54a	2.45b
1995	5.34c	8.25a	9.01a	6.83b
1996	5.35c	11.16a	11.51a	8.13b
1997	2.02c	8.49a	9.48a	3.77b
1998	4.84d	8.62b	10.59a	6.52c

[a] DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.
[b] The treatments with the same letters do not display a significant difference between them using the Newman Keul's test at 5%.

3.4. Carbon inputs through plant biomass

There was a strong inter-annual variability in maize aboveground biomass production and grain yield, mainly due to the variation in annual amounts and distribution of rainfall (Tab. VI). Aboveground biomass and grain yield were very poor in 1994 due to the very low rainfall in that year (299 mm). On the other hand, aboveground biomass and grain yield were highest in 1996, when total rainfall was 576 mm and evenly distributed throughout the growing season. Each year direct seeding mulch-based cropping resulted in a significant increase in maize yield. The relative increase was lower in drier compared with wetter years, and the beneficial effect of direct seeding mulch-based cropping was especially pronounced in the year with stormy rainfall (1997). These results suggest that the effects of direct seeding mulch-based cropping on grain yield and biomass production are principally short-term, mainly due to a better use of available soil water. On the contrary, the data do not suggest any trend in increased aboveground biomass or grain yield over the years under direct seeding mulch-based cropping, despite the significant increase in soil organic matter of the topsoil layer.

The input of organic carbon to the soil was in part defined by the experimental setup: aboveground residues had been

Table VII. Average annual maize biomass and carbon inputs to soil for the different tillage and residue management treatments in La Tinaja, Mexico from 1994 to 1998.

	Soil management			
	DS-0[a]	DMC-1.5	DMC-4.5	CT
Total aboveground biomass (Mg DM ha^{-1} year^{-1})	4.06	7.95	9.23	5.54
Crop residues retained on field (Mg DM ha^{-1} year^{-1})	0	1.5	4.5	0
Total belowground biomass (Mg DM ha^{-1} year^{-1})[b]	2.03	3.98	4.61	2.77
Total carbon inputs (Mg C ha^{-1} year^{-1})[c]	0.91	2.47	4.10	1.25

[a] DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.
[b] Calculated as 50% of the total aboveground biomass (Balesdent and Balabane, 1996).
[c] Calculated as 45% of the dry matter.

totally removed in the SD-0 and CT treatments and redistributed in the other treatments (DMC-1.5 and DMC-4.5) according to their respective amounts of 1.5 and 4.5 Mg ha^{-1}. Another part of the carbon input comes from belowground biomass production. These were for each treatment estimated based on the observed values of aboveground biomass (Tab. VI) and by assuming that the belowground biomass production of maize including root turnover and exudates can reach about 50% of the aboveground biomass (Balesdent and Balabane, 1996). We then calculated the annual total carbon input for each treatment. They were about 1, 2.5 and 4 Mg C ha^{-1} year^{-1} in the DS-0 and CT, DMC-1.5 and DMC-4.5 treatments, respectively (Tab. VII).

3.5. Carbon losses through soil erosion

Due to high costs and constraints with analytical equipment, it was not possible to analyze carbon in runoff water and sediments. Hence, we do not have precise figures on carbon erosion losses. We, therefore, approximated these losses by multiplying for each tillage and residue treatment soil carbon concentrations in the 0–2.5 cm topsoil layer as measured during 1998 in experiment C (Tab. IV) with the quantities of soil eroded (Fig. 3). Since we applied soil carbon concentrations of 1998 to soil erosion losses of 1995, 1996 and 1997 without adjusting for concentration changes over the period between 1995 and 1998, we most likely overestimated carbon losses in the DMC treatments compared with those in the treatments with no mulch. In spite of this, calculated carbon erosion losses in the treatments with direct seeding mulch-based cropping were considerably lower than those in other treatments (Tab. VIII). As expected, the differences between treatments were most pronounced in 1997, the year with intense rainfall. In that year treatments without a mulch of crop residues lost about 800 kg C ha^{-1} i.e. an amount 2 to 7 times larger than in the treatments under direct seeding mulch-based cropping. Another factor that may contribute to the higher carbon losses in conventional tillage systems is the fact that mineralization of soil organic matter is accelerated through increased aeration

Table VIII. Effect of tillage and residue management treatments on annual carbon erosion losses (Mg ha^{-1} year^{-1}) in La Tinaja, Mexico during 1995, 1996 and 1997.

Year	Tillage/residue treatments			
	DS-0[a]	DMC-1.5	DMC-4.5	CT
1995	0.048	0.019	0.012	0.025
1996	0.545	0.203	0.090	0.205
1997	0.816	0.410	0.112	0.787

[a] DS-0 = direct sowing with no mulch, DMC-1.5 = direct sowing with 1.5 Mg ha^{-1} mulch, DMC-4.5 = direct sowing with 4.5 Mg ha^{-1} mulch, CT = Conventional disc tillage.

(Reicoski, 1997) and through breakdown of soil macro-aggregates with exposure of previously physically-protected organic matter to soil organisms (Balesdent et al., 1990; Six et al., 1999). This probably explains the observed difference in soil carbon storage (1.4 Mg C ha^{-1}, Tab. V) between the SD-0 and CT treatments.

3.6. Soil carbon storage

In the simplest terms, the evolution of soil carbon stocks in agro-ecosystems are governed by the difference between inputs of organic matter through crop residues, roots, animal manure, etc., and losses of soil organic matter through mineralization and erosion. Differences in soil carbon storage between tillage and residue treatments may be explained by differences in carbon inputs, losses, or both.

After five cropping seasons carbon stocks under DMC-1.5 and DMC-4.5 increased, respectively, by 2.8 Mg C ha^{-1} (+ 0.56 Mg C ha^{-1} year^{-1} on average) and 3.9 Mg C ha^{-1} (+ 0.78 Mg C ha^{-1} year^{-1} on average) compared with the DS-0 treatment (Tab. V). On the other hand, carbon stocks decreased by 1.4 Mg C ha^{-1} (– 0.28 Mg C ha^{-1} year^{-1} on average) after five years of conventional tillage (CT) when compared with the direct seeding treatment with no mulch (DS-0). These results illustrate the potential of direct seeding mulch-based cropping systems to enhance soil carbon storage in maize production systems of semi-arid Mexico. Various studies conducted under a wide range of climatic conditions have demonstrated the beneficial effects of minimum- or no-tillage systems with intensified cropping in sequestering soil carbon (West and Post, 2002). In general, direct seeding mulch-based cropping systems enhance soil carbon storage by increasing carbon inputs to the soil, reducing carbon losses due to soil erosion and by decreasing decomposition of soil organic matter as a result of reduced mechanical soil disturbance (Erenstein, 2002; Lal and Kimble, 1997; Paustian et al., 1997).

Our study clearly illustrates the importance of considering erosion losses, when explaining differences in carbon stocks between direct seeding mulch-based cropping and conventional tillage systems. The differences in soil carbon stocks between treatments were high, particularly because of the decreasing carbon erosion losses with change from SD-0 or conventional tillage to direct seeding mulch-based cropping (Tab. VII). Soil carbon changes that are calculated as the difference between direct seeding mulch-based cropping and

SD-0 or conventional tillage using soil samples at year 5 are not only caused by an increase in soil carbon under direct seeding mulch-based cropping, but also by a decrease in soil carbon over the 5 years under conventional tillage or DS-0. The soil carbon storage rate using this method will therefore be higher than when the difference is calculated between the initial soil carbon content at the start of the experiment (year 0) and the soil carbon content at the end of the experiment (year 5).

Direct seeding mulch-based cropping systems without tillage are able to enhance soil carbon storage relative to cropping systems with conventional tillage due to increased stability and amounts of macro-aggregates (Feller and Beare, 1997; Six et al., 2002; Tisdall and Oades, 1982). It is, therefore, expected that this stabilized carbon in macro-aggregates is rather precarious, since it is mainly stored in the top 5-cm soil layer, and probably a large part of it is highly susceptible to mineralization in the case of an occasional surface tillage operation (Angers et al., 1993). However, Six et al. (1999) found that the greater carbon stabilization with direct seeding mulch-based cropping relative to conventional tillage is only partly explained by a greater amount of macro-aggregates and suggested that a reduced rate of macro-aggregate turnover under direct seeding mulch-based cropping increases the formation of micro-aggregates in which carbon is stabilized in the long term.

The potential of direct seeding mulch-based cropping for sequestering soil carbon is expected to be smaller in semi-arid relative to (sub) humid regions, because of the smaller biomass production under drier conditions. In direct seeding mulch-based cropping systems on Oxisols in sub-tropical humid southern Brazil (Sá et al., 2001), inputs of carbon through crop residues were estimated to be about 9 Mg ha^{-1} $year^{-1}$. On the other hand, carbon losses through mineralization are expected to be higher under tropical humid conditions, due to the more favorable conditions for decomposition. In their study, Sá et al. (2001) estimated that direct seeding mulch-based cropping systems in (sub) tropical regions can sequester about 0.86 Mg C $ha^{-1}year^{-1}$ (0–20 cm depth). McConkey et al. (2003) found that the soil carbon increase with adoption of direct seeding mulch-based cropping was approximately 0.3 Mg C ha^{-1} $year^{-1}$ in the semi-arid region of the Canadian prairie and approximately 0.8 Mg C ha^{-1} $year^{-1}$ in the sub-humid region of the prairie.

Direct seeding mulch-based cropping practices clearly had beneficial short-term impacts on maize yield and biomass production in La Tinaja (Tab. VI). Given the semi-arid conditions, the water-conserving effect of mulching is probably the most important process that explains the increase in crop production under direct seeding mulch-based cropping in the region. Other factors that may contribute to higher productivity in the short term are increased soil biological activity (Hoflich et al., 1999) and a larger volume of soil colonized by roots (Scopel et al., 2001), which both enhance nutrient availability and improve soil structure (Balota et al., 2004; Kandeler et al., 1999). On the other hand, the long-term productive benefits that may result from increased soil organic matter and decreased soil erosion were not (yet) obvious from our data.

Smallholder farmers will probably find it more important to reduce production risks and yield variations in the short term than achieve long-term goals such as build-up of soil fertility (Pearce and Turner, 1990). The short-term return through the water-conserving effect by mulching is thus a promising factor for adoption of direct seeding mulch-based cropping in semi-arid regions. The actual development and adoption of direct seeding mulch-based cropping will, however, depend on a number of other (including socio-economic) factors, such as the need for fodder or fuel production, management skills and constraints in acquisition of new implements.

4. CONCLUSION

Direct seeding mulch-based cropping systems – even with small amounts of surface crop residues – are very effective at conserving water under the semi-arid conditions of western Mexico. In particular, water losses through runoff are considerably reduced under direct seeding mulch-based cropping. Soil erosion losses, including losses of soil organic matter, which are linked to water runoff, are reduced by more than half under direct seeding mulch-based cropping systems relative to conventional tillage systems. Soil carbon levels increased over a 5-year period under direct seeding mulch-based cropping compared with conventional tillage both through increased carbon inputs (part of the crop residues are left on the soil surface) and reduced carbon losses (less erosion and possibly reduced mineralization). The increase in soil carbon under direct seeding mulch-based cropping principally occurs in the top 5 cm of the soil profile. Over 5 years, the positive impacts of direct seeding mulch-based cropping on maize productivity tend to be short-term, principally through improved water (and nutrient) use efficiency. The potential yield benefits in the longer term due to build-up of soil organic matter and reduction of soil erosion were not (yet) obvious. Hence, the more efficient use of available water with direct seeding mulch-based cropping is likely to reduce production risk for farmers in the semi-arid regions. Direct seeding mulch-based cropping may therefore offer fast returns to farmers. Finally, if in the future in Mexico the use of chemical fertilizer decreases due to a halt in fertilizer subsidies, the role of soil organic matter in sustaining the productivity of maize in the region will become more pronounced. This will make direct seeding mulch-based cropping an even more attractive management option for Mexican smallholder farmers.

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