No-tillage permanent bed planting and controlled traffic in a maize-cotton irrigated system under Mediterranean conditions: Effects on soil compaction, crop performance and carbon sequestration

Patricio Cid[a], Inmaculada Carmona[a], José Manuel Murillo[b], Helena Gómez-Macpherson[a]*

[a] Instituto de Agricultura Sostenible, Consejo Superior de Investigaciones Científicas (IAS-CSIC), Cordoba, Spain

[b] Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS-CSIC), Seville, Spain

*Corresponding author at: IAS-CSIC, Alameda del Obispo, s/n, 14004, Cordoba, Spain. Tel.: +34-957499276; fax: +34-957499252; E-mail address: hgomez@cica.es (H. Gómez-Macpherson)

RESEARCH HIGHLIGHTS

- We studied permanent (PB) and conventional (CB) bed systems, and controlled traffic
- Crops in CB, PB and decompacted PB (DPB) behaved similarly above ground
- In PB and DPB, compaction by traffic reduced root density in the 0.6-m topsoil
- Root density below 0.6 m depth was higher in PB than in CB despite topsoil compaction
- After 6 years, SOC stock (top 0.5-m layer) was 5.7 Mg ha^{-1} higher in PB than in CB

ABSTRACT

Under irrigated Mediterranean conditions, no-tillage permanent bed planting (PB) is a promising agriculture system for improving soil protection and for soil carbon sequestration. However, soil compaction may increase with time up to levels that reduce crop yield. The aim of this study was to evaluate the mid-term effects of PB on soil compaction, root growth, crop yield and carbon sequestration compared with conventionally tilled bed planting (CB) and with a variant of PB that had partial subsoiling (DPB) in a *Typic Xerofluvents* soil (Soil Survey Staff, 2010) in southern Spain. Traffic was controlled during the whole study and beds, and furrows with (F+T) and without traffic (F-T), were spatially distinguished during measurements. Comparisons were made during a crop sequence of maize (*Zea mays* L.)–cotton (*Gossypium hirsutum* L.)–maize, corresponding to years 4-6 since trial establishment. After six years, soil compaction was higher in PB than in CB, particularly under the bed (44 and 27% higher in top 0.3- and 0.6-m soil layers, respectively). Around this time, maize root density at early grain filling was 17% lower in PB than in CB in the top 0.6-m layer. In DPB, the subsoiling operation was not effective in increasing root density. Nevertheless, root density appeared to maintain above-ground growth and yield in both PB and DPB compared to CB. Furthermore, at the end of the study, more soil organic carbon was stocked in PB than in CB and the difference increased significantly with a depth down to 0.5 m (5.7 Mg ha^{-1} increment for the top 0.5-m soil layer). Residues tended to accumulate on furrows, and this resulted in spatial and temporal differences in superficial soil organic carbon concentration (SOC) in the permanent planting systems. In PB, SOC in the top 0.05-m layer increased with time faster in furrows than on beds, and reached higher stable values (1.67 vs. 1.09% values, respectively). In CB, tillage homogenized the soil and reduced SOC in the top 0.05-m layer (average stable value of 0.96% on average for beds and furrows).

Keywords: Conservation agriculture, No-tillage, Root density, Crop residue

1. Introduction

Maize is the most important irrigated cereal crop in southern Europe in terms of surface and production (IEEP, 2000). The development of sprinkler and drip irrigation has resulted in an expansion of maize cultivation on a hilly terrain and, with this expansion, the risk of soil erosion has increased thus becoming a major environmental concern. Conservation tillage and residue retention are expected to protect the soil and reduce its erosion (Brouder and Gómez-Macpherson, 2014). However, adoption of any form of conservation agriculture is minimal in irrigated cereal-based systems in Mediterranean environments, mostly because of soil compaction and difficulties in managing crop residues (Gómez-Macpherson et al., 2009).

Irrigated, permanent bed planting (PB) is a form of conservation tillage that could help to manage the large amount of crop residues (Boulal et al., 2012). PB has been studied in Australia (Hulugalle et al., 2010), China (He et al., 2008), India (Ram et al., 2012), Mexico (Verhulst et al., 2011a,b) and Uzbekistan (Ibragimov et al., 2011; Devkota et al., 2013) although its impact on crop yield is not clear. In previous studies, positive, negative or no effects have been reported (Devkota et al., 2013; Boulal et al., 2012; Ibragimov et al., 2011; Govaerts et al., 2005; Ram et al., 2012).

Compared to conventional systems, where crop residues are baled, burned or buried during soil preparation, managing the large amount of residues produced in irrigated PB systems is a challenge, particularly at sowing. On one hand, crop residues decrease soil temperature at emergence and may result in poorer crop establishment (Ibragimov et al., 2011; Ram et al., 2012). On the other, the maintenance of residues is a key element in conservation tillage systems because crop residues directly protect the soil and reduce soil erosion (Boulal et al., 2011b) while promoting SOC accumulation (Verhulst et al., 2010), which, in turn, may increase soil carbon sequestration (Palm et al., 2014). Some authors have argued, however, that incorporating crop residues into the soil in conventional systems would result in increasing SOC in deeper soil layers, and, thus, deeper samplings are needed to detect differences between tillage systems (Baker et al., 2007; Blanco-Canqui and Lal, 2008; Govaerts et al., 2009). In Spain, most studies on soil carbon sequestration have been carried out under rainfed conditions and for shallow horizons (Alvaro-Fuentes and Cantero-Martínez, 2010; González-Sánchez et al., 2012). Nevertheless, differences would be expected in irrigated systems because of the larger amount of crop residues produced and the higher soil moisture and temperature during summer.

PB may also result in greater soil compaction (Verhulst et al., 2011b; Ram et al., 2012) although, when combined with controlled traffic, compaction can be confined successfully to certain furrows (Chamen et al., 1992; Li et al., 2007). Controlled traffic results in spatial variations in soil water infiltration and other soil properties (Blanco-Canqui et al., 2010; Gasso et al., 2013; Cid et al., 2013) but it is not clear how soil properties will evolve in the long-term and how these properties will affect crop performance (Botta et al., 2007). Soil compaction may reduce root growth without affecting above-ground growth or yield (Busscher and Bauer, 2003; Moreno et al., 2003), provided water and nutrient availability is adequate and there is a minimum root density (Guan at al., 2014). Other authors, however, suggest that soil strength directly induces a hormonal signal that reduces shoot growth without decreases in water or nutrient availability, at least in early stages (Masle and Passioura, 1987).

PB combined with controlled traffic in an irrigated maize-cotton rotation has resulted, in the short-term, in being a successful practice for protecting the soil and increasing superficial SOC, while maintaining crop yields (Boulal et al., 2012). Our working hypothesis is that this success can be sustained in the mid-term and, in the case of carbon sequestration, confirmed with deeper soil sampling. Although PB planting systems have been developed and tested around the world, we have not identified any studies under Mediterranean conditions, and we are not aware of any example in which PB has been associated with controlled traffic. The objective of this study was, therefore, to compare mid-term effects of PB and conventional bed plantings, both combined with controlled traffic, on soil compaction, SOC, and on below- and above-ground crop performance. Additionally, a decompaction treatment in PB was also evaluated as a complementary management practice for the system.

2. Materials and methods

2.1. Experimental site, planting systems, and farming operations

The study was conducted at Alameda del Obispo experimental farm (37° 51’ N, 4° 47’ W; altitude 110 m), in Córdoba, Spain. The climate is Mediterranean with a mean annual temperature of 17.6 °C and mean annual rainfall of 536 mm, most of which is concentrated between late autumn and early spring. Figure 1 shows daily temperature and precipitation (rainfall and irrigation) during the study. The soil is a loamy alluvial, *Typic Xerofluvents* (Soil Survey Staff, 2010), of negligible shrinkage and without any apparent restriction to root growth to a depth of 3m. Particle-size distribution consisted of 390, 470 and 140, and 470, 410 and 120 g kg^{-1} sand (0.05-2 mm), silt (0.002-0.05 mm) and clay (<0.002 mm), in the 0-0.5 m and 0.5-1.0 m soil layers, respectively. Estimated water storage at field capacity was 0.24 m^{3}m^{-3}, and at wilting point, 0.12 m^{3}m^{-3}.

Figure 1 about here

This study was conducted during three years (2010–2013) as part of a long-term trial set up in 2007 to compare no-till bed planting (conservation tillage) and mulch-till conventional-bed planting systems (ASABE Standards, 2005), both combined with controlled traffic, in a maize–cotton rotation. Details of land previous history are available in Boulal et al. (2012). In 2010, part of the PB plots was modified to add a third treatment (Fig. 2). The three studied bed planting systems were: (*i*) conventional beds with plant residues incorporated during soil preparation and beds formed every year (CB); (*ii*) permanent beds with crop residues retained on the surface (PB); and (*iii*) a variant of PB in which a subsoiling operation was carried out before sowing (decompacted permanent-bed planting system, DPB).

In 2007, the experiment was laid out in a randomized complete block design with three replications, covering 0.8 ha in all (Boulal et al., 2012). From 2007 to 2009, the three blocks had two plots, each of them consisting of ten 0.85-m-spaced furrow–bed sets with either CB or PB established. Furrows were 144 m long and had an average slope of 0.4%. In March 2010, the three plots devoted to PB treatment were subdivided, and DPB was established in one side, occupying four furrow–bed sets (Fig. 2). The remaining six furrow–bed sets continued as PB. The separation between two contiguous trafficked furrows (1.7 m) was imposed by the space within the wheels of the tractor used (model *ME9000 DTL*, Kubota Corporation, Thame, UK). Beds in both PB and DPB were not reshaped since they were formed in 2007.

Traffic was controlled in the whole experiment, and furrows with wheel traffic (F+T) alternated with furrows without traffic (F-T). In CB, traffic was random during tillage for soil preparation but controlled after the beds were formed. Sowing and slashing operations affected every single F+T furrow. Although the application of fertilizers and pesticides had wider operating widths and affected a fewer number of F+T furrows, these operations started at different points in the plot to equalize, as much as possible, the number of passes per F+T furrow. In DPB, one extra wheel pass was implemented in F+T during the subsoiling operation. For a given season, wheel passes affected F+T furrows five to seven times (one more in DPB), depending on the crop. All operations were applied at the same time except subsoiling in DPB and primary and secondary tillage in CB.

Details on planting systems, farming practices, and machinery traffic from 2007 to 2009 can be consulted in Boulal et al. (2012). Features of the main farming operations carried out from late 2009 to late 2012 are shown in Table 1. Maize was cultivated in 2010 and 2012 and cotton in 2011. In 2010, maize sowing density was increased to reduce bird damage at emergence while, in 2012, protective nets allowed the use of conventional seed density. All operations except harvesting (done manually) were performed with a tractor. The main tractor used was the *Kubota ME9000* (2.9 Mg in weight; 61 kW; front wheel: radial, 11.2R20, 190 kPa inflation pressure, 81 kPa ground pressure, 9.1 kN axle load; rear wheel: 380/85R28, 150 kPa inflation pressure, 70 kPa ground pressure; 23.7 kN axle load). A second tractor (*Kubota M120 DT*; 4.1 Mg in weight; front wheel: radial, 420/70R24, 190 kPa inflation pressure, 64 kPa ground pressure; rear wheel: 480/70R38, 150 kPa inflation pressure, 80 kPa ground pressure) was used during CB subsoiling, disc ploughing, and harrowing.

Figure 2 about here

Soil water storage was monitored with a neutron probe (*503DR Hydroprobe*, CPN International Inc., Martinez, USA) before sowing, one day prior to each irrigation, and at harvest. Five access tubes (1.95 m) per plot were installed in the centre of beds of two blocks (30 tubes total). Plot soil was homogeneous, and the number of tubes was considered adequate for estimating soil moisture. Additionally, this number made it possible to complete all measurements in one day. Crops were irrigated with a sprinkler system. The amount of water to be applied per irrigation was calculated according to Allen et al. (1998) using the average calculated requirement of the three tillage treatments, and corrected by weekly measured plant height and canopy coverage in four sites per plot. Different water application per treatment was not possible because of restrictions associated with the irrigation system design.

Table 1 about here

2.2. Crop and residue measurements

Every season, four manual samplings of crop plants were carried out to determine above-ground dry matter (AGDM). In each sampling (17 May, 1 June, 22 June, and 24 July in 2010; 17 June, 11 July, 1 August, 22 August, in 2011; and 10 April, 10 May, 29 May, and 25 June in 2012), plants in 1.7 m^2 were collected in four sites per plot. No border was considered between PB and DPB. Maize grain yield was determined from hand-harvested samples (8.5 m^2) in five sites per plot. In each sampling, one fifth (1.7 m^2) was harvested separately to determine the harvest index (ratio of grain dry mass and above-ground biomass), the number of ears per plant, number of kernels per ear, and 1000-kernel weight. AGDM was estimated from grain yield and harvest index. Yield of cotton seed (including the lint) was determined by hand picking (9.4 m^2) in four sites per plot. In one-fourth (2.35 m^2), above-ground matter and yield components were also determined. The above ground parts were dried at 75 °C to constant weight.

Maize root density was measured at the early grain-filling period in late July - early August in 2012. The study was carried out following the trench-excavated method (van Noordwijk et al., 2000) using a backhoe loader that opened a single trench perpendicular to crop rows in blocks 1 and 3. A metal grid (0.9 m wide by 1 m high divided into 0.1 by 0.1 m cells) was placed on the wall of the trench under one crop row per planting treatment and block for root counting cell by cell. The column of cells under the crop row was assigned position 0. Adjacent columns of cells were assigned positions 1-4 in F+T and -1 to -4 in F-T, with positions 4 and -4 corresponding to the centre of the furrows. Before root counting, approximately 0.03 m of the vertical soil profile was scraped using a small rake to expose maize roots and facilitate their visualization. A soil core (0.05 m in height, 0.05 m in diameter) was taken horizontally using a soil corer in seven cells of the grid of contrasting root intersections in PB and CB transects (n=28). Roots contained in soil cores were gently washed using 0.063-mm-size sieve to remove mineral particles and plant debris. Roots were stained with a 1% aqueous solution of congo red to facilitate the identification of living roots during their software-assisted quantification. *WinRHIZO* (Regent Instruments Inc., Quebec, Canada) was used to quantify the total root length in each root sample. The relationship obtained between root frequency and root density was used to transform root frequency into root density values.

The weight of plant residues in F+T and F−T furrows (0.59 m × 0.50 m) and on the bed (0.26 m × 0.50 m) was determined from four sites per plot using a rectangular frame. After removing the attached soil, the samples were washed under a spray nozzle at the lowest force without splashing. Samples were dried at 75 °C to constant weight and mass per unit area was calculated. Samplings took place on 13 May and 22 October in 2011, and 30 March and 20 November in 2012. Digital photos of the framed area were taken before collecting the residues. The photos were processed with ENVI 4.7 software (Environment for Visualizing Images, Research Systems. Inc, CO, USA) to determine the percentage of soil covered by residues.

2.3. Soil physical and chemical measurements

Soil cone index (CI) was measured with a penetrometer (model HINKA-2010 v1.0, Agrosap S.L., Spain) with a 30° steel cone with a base diameter of 0.01283 m (ASAE Standard S313 [ASABE

Standards, 1999]) coupled to a portable computer. CI was measured in beds and adjacent trafficked and untrafficked furrows in three sites per plot (five measurements per site) in May, August, and December 2011, and in November 2012. CI was also measured in bed shoulder positions, i.e., in between the centre of the bed and the centre of the furrow, in the November 2012 sampling. Measurements were taken to a depth of 0.6 m, except in August 2011 (0.3 m) due to excessive soil strength, in all cases with readings in 0.05 m increments. Volumetric soil water content (SWC) of the top 0.6-m layer (0.3 m in May 2011) was measured concurrently in all sites, with a time domain reflectometry (TDR) device (MiniTrase System; SoilMoisture Equipment Corp., Santa Barbara, USA).

Soil bulk density (ρ) was measured in the centre of beds and adjacent furrows, at three sites per elemental plot, for the depth layers 0.05-0.1, 0.2-0.25, 0.35-0.4, 0.5-0.55, and 0.65-0.7 m, using a cylinder 0.05-m in diameter 0.05-m high. Samples were oven-dried at 105 °C for 48 h. Samplings were carried out in June 2011 and January 2012,

Soil samples for determining SOC concentration were taken in the 0–0.05, 0.05–0.10, and 0.10–0.30m layers, in the beds and their adjacent F+T and F-T furrows. Six samples were taken in each elemental plot to form a composite sample. Sampling was done on 19 April 2011, 23 January 2012 and 22 November 2012. A second sampling was conducted in CB on 6 June 2011 (40 days after tillage). Samples were air-dried and passed through a 2-mm sieve. SOC concentration was determined according to Walkley and Black (1934).

In the last sampling at the end of the study (November 2012), soil sampling was carried out down to 1-m depth in PB and CB treatments only. SOC concentration was determined for each 0.1-m layer. SOC concentration was converted into SOC stock per unit area (SOCs) considering ρ and the thickness of the horizons. The global amounts of SOCs expressed in Mg ha^{-1} were obtained by adding values of layers (Schwager and Mikhailova, 2002).

2.4. Statistical analysis

Data for yield and yield components were analyzed by ANOVA considering a randomized block design in spite of DPB being nested in PB. Data for soil *ρ*, CI and SOC concentration were analyzed within bed or furrows positions and soil layers. SOCs corresponding to a certain planting system was calculated by weighing the values obtained in bed, and furrows (bed 50% and F+T and F-T furrows 25% each). Mean values were separated using the Tukey's HSD means comparison test with a significance level of 5%. Statistical analyses were carried out using Statistix 9.0 (Analytical Software, Tallahassee, FL, USA).

3. Results

3.1. Soil compaction

Differences in CI with soil depth and treatments were relatively consistent over time. Data are presented for the last sampling (November 2012) only (Fig. 3) as the soil would show the accumulated effects of all traffic operations during the study. This sampling also included additional measurements in the bed shoulder (S), an intermediate position between the bed and the furrow. In general, CI was lower in CB than in PB. Average CI for the 0.6-m profile in the bed positions was 27% lower in CB than PB (44% lower for the top 0.3 m). Except in F+T, the soil profile also tended to be less compacted in CB than in PB in the rest of positions: 21, 9 and 15% less in S+T, S-T and F-T, respectively, for the 0.6-m profile (38, 25 and 20% less for the top 0.3-m layer). Soil moisture (0-0.6 m) measured the same day in bed and furrows positions did not differ between treatments or positions (Fig. 3).

Wheel traffic increased CI in F+T and adjacent S+T shoulder (Fig. 3). In DPB, subsoiling was effective in decompacting F+T soil down to 0.30 m depth, although this operation created a soil pan below this depth and did not have any effect on loosening the shoulder soil.

Soil bulk density (ρ) measurements greatly varied between samples and significant differences were hardly detected (data not shown). In general, ρ was lower in CB than in PB, particularly in beds and for the top 0.3 m layer (1.36 and 1.45 g cm^{-3}, respectively, in the last sampling in January 2012). In furrows, wheel traffic increased ρ significantly in the top 0.3-m layer, but no differences were detected between PB and CB: 1.59 g cm^{-3} and 1.49 g cm^{-3} average for both plantings in F+T and F-T, respectively. In DPB, subsoiling resulted in 7% lower ρ in the F+T top 0.15 m layer compared to PB.

Figure 3 about here

3.2. Crop growth and yield

In the maize crop, AGDM tended to accumulate faster in CB than in PB or DPB at the beginning of the cropping season (data not shown). These differences were maintained over time until maturity in 2010 but disappeared in 2012 (Table 2). Similarly, in 2010, grain yield was significantly higher in CB (and DPB) than in PB but did not differ between planting systems in 2012. Compared with CB, PB plots at maturity in 2010 had a lower plant height and grain biomass per ear but a similar kernel weight.

In the cotton crop, AGDM accumulation during the 2011-growing season did not differ between planting systems (data not shown) except at harvesting, when AGDM was significantly higher in DPB than in CB, with no differences between them and PB (Table 2). The higher biomass did not result in a higher seed yield (seed plus lint) or yield components.

Table 2 about here

Below-ground crop growth was studied only in the 2012 maize crop, at the early grain-filling period (milk dough stage). Contrary to above-ground crop growth, root density differed between planting systems (Fig. 4). CB had 7% higher root density than PB for the whole studied profile (from the centre of a furrow with traffic to the centre of the adjacent furrow without traffic by 1 m depth). Differences were mostly observed in the upper 0.6-m layer (17% higher density), particularly at positions in furrows without traffic (Fig. 4a). Root density decreased with depth, and more markedly in CB than in PB, particularly at the same positions without traffic influence (Fig. 4b). Root density in the deeper 0.6-1.0-m layer was 14% higher in PB than in CB.

Root density was highest under the plant row and decreased with distance towards the centre of furrows. Wheel traffic had a greater effect on root density in PB than in CB (on average, 26% lower density for positions 0 to +4 in the top 0.6-m layer), and more in DPB than in PB (29% lower density on average for the same section).

Figure 4 about here

3.3. Crop residues and ground coverage

The evolution of crop residue biomass in bed/furrow positions by PB and DPB planting systems since the trial's establishment in 2007 is presented in Fig. 5. A larger amount of plant residues accumulated in furrows relative to bed positions, except when most crop residues were still standing, as in October 2009 and March 2010, when standing cotton stalks represented approximately 85% of crop residues, or immediately after slashing maize stalks, as in November 2012 when the stubble was homogeneously dispersed across positions. After six years of no-tillage, the bed shape had practically disappeared, and crop residues were displaced into furrows mostly during the sowing operation. Regarding wheel traffic, no clear effect was observed on the amount of crop residues on the ground when F+T and F-T were compared; nor was any significant effect observed of the subsoiling operation on F+T in DPB relative to the equivalent undisturbed F+T furrows in PB.

In CB, crop residues were on the ground between harvest and soil preparation so that they protected the soil during autumn and most of the winter. Crop residues were incorporated with tillage into the soil during soil preparation in early spring.

Soil protection depends more on the ground surface covered by crop residues than on their biomass. We did not find any relationship between the amount of plant residues and ground covered except in the March 2010 sampling in the CB system when ground cover was lower than 30%, and soil preparation had not taken place yet (Fig.6). In autumn, ground cover was always above 50% in PB and CB and crop residue biomass varied from 3 to 12 Mg ha^{-1}. In spring, the percentage decreased to less than 50% although, in the case of the PB system, values remained above 30% with crop residue biomass that varied from 2.8 to 9 Mg ha^{-1}. In DPB, subsoiling in F+T reduced the surface covered below 30% on some occasions (six out of 18 points) with biomass of above 3 Mg ha^{-1}.

Figure 5 about here

Figure 6 about here

3.4. Soil organic carbon

Soil organic carbon concentration (SOC) was measured down to 0.3 m twice a year, except for the last sampling, in which the depth was 1 m. Most differences between planting systems or bed/furrow positions were found in the top 0.05-m layer. Therefore, we have presented the evolution of SOC concentration with time for this top layer only. The stock of soil organic carbon (SOCs), and estimated soil carbon sequestration, is given for deeper layers in the last sampling to show the accumulated effect with time.

SOC concentration in the top 0.05-m soil layer ($SOC_{0.05}$) increased with time since the beginning of the experiment in 2007, but it did so differently depending on planting systems and bed/furrow positions (Fig. 7). During the first four years, $SOC_{0.05}$ increased faster in PB furrows (both with and without traffic) than in beds, 0.326 and 0.120% y^{-1}, respectively, (F+T is shown only for easier comparison with subsoiled F+T in DPB). Furthermore, $SOC_{0.05}$ in furrows became stabilized at significantly higher concentrations than in beds: 1.67% and 1.09% concentrations, respectively, on average for the last three samplings. The average $SOC_{0.05}$ value for the last three samplings in decompacted F+T (DPB) was 1.52%.

$SOC_{0.05}$ also increased in CB during the first four years (0.096 % y^{-1}) at a similar rate to that in PB beds, to reach a relatively stable value of 0.96% (averaged for bed and furrow positions in the last three samplings in CB). In spring 2011, the effect on SOC concentration of disturbing and mixing the soil during its preparation in CB was determined by carrying out an additional sampling 40 days after soil tillage and bed formation (data not shown). SOC had decreased 27%, on average for all positions and soil layers, compared with SOC determined on 19 April 2011 (eight days before soil tillage and bed formation).

Figure 7 about here

Stock of soil organic carbon (SOCs) was also calculated in PB and CB down to 1 m (Fig. 8) using soil ρ and SOC concentration determined at the end of the study. Rather than being diluted, significant differences in SOCs between PB and CB increased as thicker soil layers were considered, e.g. SOCs was 4.7, 5.4 and 5.7 Mg ha^{-1} higher in PB than CB in the top 0.1-, 0.3- and 0.5-m soil layers, respectively. Differences continued to increase with thicker layers but not significantly. Considering the entire 1-m profile, SOCs was 74 and 66 Mg ha^{-1} in PB and CB, respectively.

Figure 8 about here

4. Discussion

4.1. Effect of planting systems on soil compaction and crop growth and yield

The absence of tillage in PB resulted in higher cone index (CI) values in PB than in CB, particularly in bed and shoulders (Fig. 3), most probably as a result of soil compaction, as there were no differences in soil moisture between treatments (Mulqueen et al., 1977). The higher CI values in PB, followed by DPB and then by CB, led us to believe that no-tillage had reached compaction levels in 2010 that limited crop growth and yield in PB (Table 2). However, no differences in cotton seed yield (seed plus lint) were observed between planting systems in the following season, in spite of the high susceptibility of the root system of this crop to soil compaction (Materechera et al., 1991), nor were there any differences in maize yield in 2012 despite differences in CI.

The reasons for the low values of AGDW and yield in PB in 2010 are not clear. Slow early crop growth in no-tilled systems has been observed by others but crops often recover to match or surpass grain yield obtained in conventionally tilled crop systems (Cassel et al. 1995; Verhulst et al., 2010). At maturity, PB plots had one plant less per unit area and lower total plant biomass, biomass per ear, and plant height compared with CB, but similar kernel weight (Table 2). These differences indicate that the source of variation most probably occurred before grain filling and in association with water or nutrient stress. The water balance calculated for irrigation scheduling suggests that crops in PB plots did not suffer drought during the season. On the other hand, unusual heavy rainfalls from December 2009 to March 2010 (747 mm accumulated) before maize sowing could have resulted in considerable nitrate leaching in this soil type (Moreno et al., 1996), particularly in PB because of its higher soil water infiltration (Boulal et al. 2011b), and this deficit might not have been compensated for with applied fertilizers.

In 2012, planting systems did not differ in maize grain yield (Table 2), which is in keeping with other studies in southern Europe that have compared conservation agriculture systems (Khaledian et al., 2010; Salmerón et al., 2011). The planting systems assessed here, however, differed in root system development. Compared with in CB, soil was more compacted in PB, and this resulted in a lesser root density, particularly under furrows with traffic (F+T) and beds and the intermediate shoulder (S+T) (Fig. 4). In the case of cotton, root growth is reduced with values of above 0.3 MPa and stops at 2.5 MPa for medium to coarse soil textures (Taylor et al., 1966). In the case of maize, root growth decreases drastically with increasing CI values of above 0.9 MPa and it practically stops at 3 MPa for a wide range of soil textures from sandy loam to silty clay loam (Imhoff et al., 2010). The maximum recorded CI value in this study was under 1.8 MPa, but measurements were taken at high soil moisture either during the irrigation campaign or during the wet winter. High soil moisture contents are typical in irrigated crops in this region, particularly in maize as it is cultivated for maximum production.

PB tended to have fewer roots than CB in the upper soil layers and more roots in deeper layers in agreement with other irrigated maize studies (Guan et al., 2014) but contrary to the most general findings in no-tilled rainfed systems, where more maize roots are observed in the top soil than in tilled soil, probably favoured by higher superficial soil moisture compared with tilled soil (Cassel et al., 1995; Dwyer et al., 1996). In irrigated systems, this advantage does not apply. In deeper layers, root growth was probably facilitated by macropores created by previous crops in PB. Up to 40% of total roots have been observed recolonizing previous pores in no-tilled maize plots (Rasse and Smucker, 1998). On the whole, root development under the crop row and F-T in PB appeared, nevertheless, to be sufficient for maintaining nutrient uptake and for sustaining similar above-ground growth and grain yield in agreement with Moreno et al. (2003).

Subsoiling in DPB did not help to substantiate if crop production in PB was limited by soil compaction. Subsoiling was effective in reducing CI in the centre of the trafficked F+T furrow down to 0.3 m but it resulted in a plough-pan at 0.3-0.4 m soil depth and it had no effect on the shoulder (S+T) compaction (Fig. 3). Since no benefits were derived from DPB (Fig. 4), another type of zone-tillage rather than the subsoiling carried out in this study may be more successful, for example, a paraplough with legs angled at 45° to the side in the seed row (López-Fando and Pardo, 2012). Further research is required to evaluate options that loosen soil and improve root growth to test if any yield improvement is possible compared to conventional systems as in Box and Langdale (1984), particularly if the adoption of controlled traffic is not possible.

4.2. Effect of planting systems on crop residues and soil organic carbon

Most crop residues in a bed planting system with widely separated crop rows (0.85 m) tended to fall onto the bottom of the furrows, particularly after slashing or sowing as has happened in the PB system since its establishment (Fig. 5). With time, beds faded in PB and crop residues were displaced towards furrows with the drill tines at sowing. Residues on the ground degraded during the relatively mild Mediterranean autumn and winter, yet, in the spring samplings, the average amount of residues during the last three seasons (2010-2012) in PB was 6.2 Mg ha^{-1}, which generally ensured values of ground cover of above 30% in the early stages of crop growth (Fig. 6). This percentage of ground cover is considered to be the minimum for protecting the soil from rainfall impact (Hobbs et al., 2008) but no specific research has been carried out for local conditions and prevailing slopes.

Although we did not find any clear relationship between crop residue biomass and the percentage of ground covered by this biomass, crop residues of above 3 Mg ha^{-1} would cover 30% or more soil ground in most cases (Fig. 6). In DPB, subsoiling had little effect on reducing crop residue biomass and soil protection was generally ensured in agreement with Cassel et al. (1995) and López-Fando and Pardo (2012). By contrast, in CB, all crop residues were incorporated into the soil during bed preparation in late winter leaving loose soil devoid of protective cover and with a high risk of water erosion at this time (Boulal et al., 2011a). Earlier in the autumn and winter, crop residues covered more than 50% ground surface in CB, particularly after the maize harvest.

The spatial and temporal differences in crop residue accumulation on the ground resulted in differences in soil organic concentrations in the top 0.05-m ($SOC_{0.05}$) soil layer (Fig. 7). In PB, $SOC_{0.05}$ accumulated faster in furrows than in beds and was stabilized at higher values: 1.67% vs. 1.09% concentrations in furrows and beds, respectively. The difference between these positions in PB is due to the larger amount of crop residues on the furrows and the slightly more favourable micro-environmental conditions (higher soil moisture, lower soil temperature during the day, and higher soil temperature at night) for microorganism activity as shown for this same site (Panettieri et al., 2013). There is a close link between the amount of crop residues and soil organic carbon provided humidity and temperature do not limit the biological processes (Karlen et al., 1994).

Wheel traffic did not affect $SOC_{0.05}$. In DPB, subsoiling practically did not affect $SOC_{0.05}$ in the centre of F+T contrary to other studies in Spain in sandy clay loam soils (López-Fando et al., 2007). In CB, tillage reduced $SOC_{0.05}$ by mixing the soil within the profile, by incorporating the stubble and favouring its decomposition, and by enhancing mineralization of organic matter (Govaerts et al., 2009). Nonetheless, since the establishment of the experiment, $SOC_{0.05}$ in CB has increased to reach a similar stable value to that in undisturbed PB beds (Fig. 7). This increase was partly due to the large amount of crop residues incorporated into the soil in the maize-cotton irrigated system compared with previous rainfed clean fallow (Boulal et al., 2012), in agreement with Wu et al. (2008), and partly due to the time of sampling, which mostly took place several months after soil preparation giving soil organic carbon an opportunity to build up in the temporarily undisturbed soil (Carter, 2002).

At the end of our study, six years after establishing the experiment, differences in SOC concentration between PB and CB were significant for the superficial soil layers only, in agreement with other local studies in rainfed cereal-based systems for a range of soil textures (Murillo et al., 2004; Hernanz et al., 2009; Madejón et al., 2009).On the other hand, soil organic carbon expressed as stock carbon (SOCs) was higher in PB than in CB and this difference increased significantly as thicker soil layers were considered, rather than being diluted. The maximum detected difference was 5.7 Mg ha^{-1} for the top 0.5-m soil layer (Fig. 8).

The difference in SOCs between PB and CB was eight times greater than that found in a short duration experiment comparing no-tilled with conventional irrigated maize in a loam soil in the region (Muñoz et al., 2007), but less than half the increment estimated by Boulal and Gómez-Macpherson (2010) for a similar PB system (maize-cotton rotation, central pivot irrigation, permanent beds and controlled traffic) compared to CB in a nearby commercial farm. The commercial plots, however, had clay loam soils with a clay content of 38%, more than double that in our study (14%). Soils with a higher clay content increase the potential to protect organic matter from microbial decomposition (Weil and Magdoff, 2004). The difference in SOCs between PB and CB was also nearly double that found, on average, in Spanish studies comparing no-tilled and inversion tillage in rainfed cereal-based systems (Alvaro-Fuentes and Cantero-Martínez, 2010). Longer-term experiments may be needed to reach saturated SOC under rainfed conditions, e.g. some local examples showed similar or even higher levels of carbon sequestration after 11 years since the systems' adoption: 8.3 Mg ha^{-1} (top 0.9-m layer) (López-Bellido et al., 2010) and 10.4 Mg ha^{-1} (top 0.52-m layer) (Ordóñez-Fernández et al., 2007), although both studies were carried out in vertisol soils with clay content of around 70%. The fast SOC accumulation under no-tillage observed under our irrigated conditions compared with rainfed systems is possible due to the higher biomass input probably overriding fast decomposition of residues expected in high moisture (irrigation) and temperature conditions during summer. Further SOCs increase may be possible by changing crops in the rotation, e.g. a low (cotton) for a high (wheat) biomass producer crop (Govaerts et al., 2009), or by increasing cropping intensity with a double crop system (Luo et al., 2010), provided N, P, and S are not limiting soil organic matter formation (Kirkby et al., 2013). The problem will lie in how to handle such large amounts of residues. Vertical tillage without soil inversion or superficial rolling harrow tillage carried out every 2-3 years may then be considered for reducing crop residue biomass.

5. Conclusion

Six years of PB resulted in higher soil compaction than CB but, by maintaining controlled traffic, compaction was mostly confined to furrows with traffic and neighbour shoulders. As a result, root density was lower in PB than in CB although not to the extent of reducing crop yield. Hence, PB combined with controlled traffic appears, in the mid-term, to be a promising conservation agriculture system in irrigated Mediterranean environments. Should compaction reach limiting levels for crop production in the future, alternative strategies to DPB would be needed.

Crop residues tend to be deposited on furrows. In PB, this spatial variation resulted in a faster increase of $SOC_{0.05}$ with time and higher saturated values in furrows than in beds. In CB, soil disturbance eliminated any spatial variation in $SOC_{0.05}$ and resulted in significant lower values than in PB furrows. Regarding SOC stock, deep soil sampling has shown that PB soil had 5.7 Mg ha^{-1} more C than CB for the top 0.5-m soil layer. Compared to rainfed conditions, this value is twice the values obtained for a similar duration and soil texture, but lower than in longer duration studies in soils with a high clay content. Some issues have thus to be addressed in order to understand the full potential of irrigated PB and controlled traffic in soil carbon sequestration. Irrigation, in principle, enables cropping intensification and higher residue production, but a better spatial and temporal characterization of soil carbon accumulation and factors limiting or promoting it, e.g. soil texture and root biomass contribution to that organic carbon accumulation, is needed for Mediterranean conditions.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. FAO Irrigation and Drainage Paper No. 56. FAO, Rome.

Álvaro-Fuentes, J., Cantero-Martínez, C., 2010. Short communication. Potential to mitigate anthropogenic CO_2 emissions by tillage reduction in dryland soils of Spain. Spanish J. Agric. Res. 8, 1271–1276.

ASABE Standards. 1999. Soil Cone Penetrometer. ASAE Standard S313. 3. ASABE, St. Joseph, MI, USA.

ASABE Standards. 2005. EP291.3 FEB2005: Terminology and Definitions for Soil Tillage and Soil-Tool Relationships. ASABE, St. Joseph, MI, USA.

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration - What do we really know? Agric. Ecosyst. Environ. 118, 1–5.

Blanco-Canqui, H., Claassen, M.M., Stone, L.R., 2010. Controlled traffic impacts on physical and hydraulic properties in an intensively cropped no-till soil. Soil Sci. Soc. Am. J. 74, 2142-2150.

Blanco-Canqui, H., Lal, R., 2008. No-tillage and soil-profile carbon sequestration: An on-farm assessment. Soil Sci. Soc. Amer. J. 72, 693-701.

Botta, G.F., Pozzolo, O., Bomben, M., Rosatto, H., Rivero, D., Ressia, M., Tourn, M., Soza, E., Vazquez, J., 2007. Traffic alternatives for harvesting soybean (Glycine max L.): Effect on yields and soil under a direct sowing system. Soil Tillage Res. 96, 145-154.

Boulal, H., Gómez-Macpherson, H., 2010. Dynamics of soil organic carbon in an innovative irrigated permanent bed system on sloping land in southern Spain. Agric. Ecosyst. Environ. 139, 284–292.

Boulal H, Gómez-Macpherson H, Gómez JA, Mateos L (2011a). Effect of soil management and traffic on soil erosion in irrigated annual crops. Soil Tillage Res. 115-116, 62–70.

Boulal, H., Mateos, L., Gómez-Macpherson, H., 2011b. Soil management and traffic effects on infiltration of irrigation water applied using sprinklers. Irrig. Sci. 29: 403–412.

Boulal, H., Gómez-Macpherson, H., Villalobos, F.J., 2012. Permanent bed planting in irrigated mediterranean conditions: short-term effects on soil quality, crop yield and water use efficiency. Field Crops Res. 130: 120–127.

Box Jr, J.E., Langdale, G.W., 1984. The effects of in-row subsoil tillage and soil water on corn yields in the Southeastern Coastal Plain of the United States. Soil Tillage Res. 4, 67-78.

Brouder S., Gómez-Macpherson, H., 2014. The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence. Agric. Ecosyst. Environ. 187, 11-32.

Busscher, W.J., Bauer, P.J., 2003. Soil strength, cotton root growth and lint yield in a southeastern USA coastal loamy sand. Soil Tillage Res. 74, 151–159.

Carter, M.R., 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agron. J. 94, 38–47.

Cassel, D.K., Raczkowski, C.W., Denton, H,P., 1995. Tillage effects on corn production and soil physical conditions. Soil Sci. Soc. Am. J. 59, 1436-1443.

Chamen, W.C.T., Watts, C.W., Leede, P.R. & Longstaff, D.J. 1992. Assessment of a wide span vehicle (gantry), and soil and crop responses to its use in a zero traffic regime. Soil Tillage Res., 24, 359-380.

Cid, P., Pérez-Priego, O., Orgaz, F., Gómez-Macpherson, H., 2013. Short and mid-term tillage-induced soil CO2 efflux on irrigated permanent and conventional bed planting systems with controlled traffic in southern Spain. Soil Sci. 51, 447–458.

Devkota, M., Martius, C., Lamers, J.P.A., Sayre, K.D., Devkota, K.P., Gupta, R.K., Egamberdiev, O., Vlek, P.L.G., 2013. Combining permanent beds and residue retention with nitrogen fertilization improves crop yields and water productivity in irrigated arid lands under cotton, wheat and maize. Field Crops Res. 149, 105–114.

Dwyer, L.M., Ma, B.L., Stewart, D.W., Hayhoe, H.N., Balchin, D., Culley, J.L.B., McGovern, M., 1996. Root mass distribution under conventional and conservation tillage. Can. J. Soil Sci. 76, 23–28.

Gasso V., Sørensen, C.A.G., Oudshoorn, F.W., Green, O., 2013. Controlled traffic farming: A review of the environmental impacts. Eur. J. Agron. 48, 66–73.

Gómez-Macpherson, H., Boulal, H., Mrabet, R., González, E., 2009. Rational and application of CA for irrigated production in southern Europe and North Africa. In: Proceedings of the 4th World Congress on Conservation Agriculture: Innovations for improving efficiency, equity and environment, New Delhi, India, pp 129–135.

González-Sánchez, E.J., Ordóñez-Fernández, R., Carbonell-Bojollo, R., Veroz-González, O., Gil-Ribes, J.A. 2012. Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. Soil Tillage Res. 122, 52–60.

Govaerts, B., Sayre, K.D., Deckers, J., 2005. Stable high yields with zero tillage and permanent bed planting? Field Crops Res. 94, 33–42.

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J., Dendooven, L., 2009. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. CRC. Crit. Rev. Plant Sci. 28, 97–122.

Guan, D., Al-Kaisi, M.M., Zhang, Y., Duan, L., Tan, W., 2014. Tillage practices affect biomass and grain yield through regulating root growth, root-bleeding sap and nutrients uptake in summer maize. Field Crops Res. 157, 89-97.

He, J., Li, H., McHugh, A.D., Ma, Z., Cao, X., Wang, Q., Zhang, X., Zhang, X., 2008. Spring wheat performance and water use efficiency on permanent raised beds in arid northwest China. Soil Research 46, 659–666.

Hernanz, J.L., Sánchez-Girón, V., Navarrete, L., 2009. Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. Agric. Ecosyst. Environ. 133, 114–122.

Hobbs, P.R., Sayre, K.D., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363, 543–55.

Hulugalle, N.R., Weaver, T.B., Finlay, L.A., 2010. Drainage under permanent beds in a furrow-irrigated Vertisol. In: 19th World Congress of Soil Science, Soil Solutions for a Changing World, Brisbane, Australia, pp 21–24.

Ibragimov, N., Evett, S.R., Esenbekov, Y., Khasanova, F., Karabaev, I., Mirzaev, L., Lamers, J., 2011. Permanent beds vs. conventional tillage in irrigated arid Central Asia. Agron. J. 103, 1002–1011.

IEEP, 2000. The environmental impacts of irrigation in the European Union. Environment Directorate of the European Commission, Brussels, Belgium (http://ec.europa.eu/environment/agriculture/studies.htm).

Imhoff, S., Kay, B.D., Pires da Silva, A., Hajabbasi, M.A., 2010. Evaluating responses of maize (*Zea mays L.*) to soil physical conditions using a boundary line approach. Soil Tillage Res. 106, 303–310.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., Jordahl, J.L., 1994. Crop residue effects on soil quality following 10-years of no-till corn. Soil Tillage Res. 31, 149–167.

Khaledian, M.R., Mailhol, J.C., Ruelle, P., Mubarak, I., Maraux, F., 2010. Nitrogen balance and irrigation water productivity for corn, sorghum and durum wheat under direct seeding into mulch when compared with conventional tillage in the southeastern France. Irrig. Sci. 29, 413–422.

Kirkby, C.A., Richardson, A.E., Wade, L.J., Batten, G.D., Blanchard, C., Kirkegaard, J.A., 2013. Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biology Biochem. 60, 77-86.

Li, Y.X., Tullberg, J.N., Freebairn, D.M., 2007. Wheel traffic and tillage effects on runoff and crop yield. Soil Tillage Res. 97, 282–292.

López-Bellido, R.J., Fontán, J.M., López-Bellido, F.J., López-Bellido, L. 2010. Carbon sequestration by tillage, rotation, and nitrogen fertilization in a mediterranean vertisol. Agron. J. 102, 310–318.

López-Fando, C., Pardo, M.T., 2012. Use of partial-width tillage system maintains benefits of no-tillage in increasing total soil nitrogen. Soil Tillage Res. 118, 32-39.

López-Fando, C., Dorado, J., Pardo, M.T., 2007. Effects of zone-tillage in rotation with no-tillage on soil properties and crop yields in a semi-arid soil from central Spain. Soil Tillage Res. 95, 266–276.

López-Garrido, R., Madejón, E., Murillo, J.M., Moreno, F., 2011. Soil quality alteration by mouldboard ploughing in a commercial farm devoted to no-tillage under mediterranean conditions. Agric. Ecosyst. Environ. 140, 182–190.

Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139, 224–231.

Madejón, E., Murillo, J.M., Moreno, F., López, M.V., Arrue, J.L., Álvaro-Fuentes, J., Cantero, C., 2009. Effect of long-term conservation tillage on soil biochemical properties in mediterranean spanish areas. Soil Tillage Res. 105, 55–62.

Masle, J., Passioura, J.B. 1991. The effect of soil strength on the growth of young wheat plants. Aust. J. Plant Physiol. 14, 643-656.

Materechera, S.A., Dexter, A.R., Alston, A.M., 1991. Penetration of very strong soils by seedling roots of different plant species. Plant Soil 135, 31–41.

Moreno, F., Cayuela, J.A., Fernández, J.E., Fernández-Boy, E., Murillo, J.M., Cabrera, F., 1996. Water balance and nitrate leaching in an irrigated maize crop in SW Spain. Agric. Water Manag. 32, 71–83.

Moreno, F., Murer, E.J., Stenitzer, E., Fernández, J.E., Girón, I.F., 2003. Simulation of the impact of subsoil compaction on soil water balance and crop yield of irrigated maize on a loamy sand soil in SW Spain. Soil Tillage Res. 73, 31–41.

Muelqueen, J., Stafford, V., Tanner, D.W., 1977. Evaluation of penetrometers for measuring soil strength. J. Terramech. 14, 137–151.

Muñoz, A., López-Piñeiro, A., Ramírez, M., 2007. Soil quality attributes of conservation management regimes in a semi-arid region of south western Spain. Soil Tillage Res. 95, 255–265.

Murillo, J.M., Moreno, F., Girón, I.F., Oblitas, M.I., 2004. Conservation tillage: long term effect on soil and crops under rainfed conditions in south-west Spain (Western Andalusia). Spanish J. Agric. Res. 2, 35–43.

Ordóñez-Fernández, R., González Fernández, P., Giráldez, J.V., Perea Torres, F., 2007. Soil properties and crop yields after 21 years of direct drilling trials in southern Spain. Soil Tillage Res. 94, 47–54.

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., Grace, P., 2013. Conservation agriculture and ecosystem services: An overview. Agricult. Ecosyst. Environ. 187, 87-105.

Panettieri, M., Carmona, I., Melero, S., Madejón, E., Gómez-Macpherson, H., 2013. Effect of permanent bed planting combined with controlled traffic on soil chemical and biochemical properties in irrigated semi-arid Mediterranean conditions. Catena 107, 103–109.

Ram H., Singh, Y., Saini, K.S., Kler, D.S., Timsina, J., Humphreys, E.J., 2012. Agronomic and economic evaluation of permanent raised beds, no tillage and straw mulching for an irrigated maize-wheat system in northwest India. Exp. Agric. 48, 21–38.

Rasse, D.P., Smucker, A.J.M., 1998. Root recolonization of previous root channels in corn and alfalfa rotations. Plant Soil 204, 203–212.

Salmerón M., Isla, R., Cavero, J., 2011. Effect of winter cover crop species and planting methods on maize yield and N availability under irrigated mediterranean conditions. Field Crops Res. 123, 89–99.

Schwager, S.J., Mikhailova, E.A., 2002. Estimating variability in soil organic carbon storage using the method of statistical differentials. Soil Sci. 167, 194–200.

Soil Survey Staff, 2010. Keys to Soil Taxonomy, 11th ed. USDA-NRCS.

Taylor, H.M., Roberson, G.M., Parker Jr., J.J., 1966. Soil strength-root penetration relations for medium-to coarse-textured soil materials. Soil Sci., 102, 18-22.

Gardner, H.R., 1963. Penetration of cotton seedlings tap root as influenced by bulk density, moisture content and strength of soil. Soil Sci. 96, 153–156.

Van Noordwijk, M., Brouwer, G., Meijboom, F., Oliveira, M.R.G., Bengough, A.G. 2000. Trench profile techniques and core break methods. In: Smit, A.L., Bengough, A.G., Engels, C., van Noordwijk, M., Pellerin, S., van de Geijn, S.C. (Eds.), Root methods. A handbook. Springer Berlin Heidelberg. pp 211-233.

Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P., Chocobar, A., Deckers, J., Sayre, K.D. 2010. Conservation Agriculture. Improving soil quality for sustainable production systems? In: Lal, R., Stewart, B.A. (Eds), Advances in Soil Science: Food Security and Soil Quality, CRC Press: Boca Raton, FL, USA, pp 137–208.

Verhulst, N., Carrillo-García, A., Moeller, C., Trethowan, R., Sayre, K.D., Govaerts, B., 2011a. Conservation agriculture for wheat-based cropping systems under gravity irrigation: increasing resilience through improved soil quality. Plant Soil 340, 467–479.

Verhulst, N., Kienle, F., Sayre, K.D., Deckers, J., Raes, D., Limón-Ortega, A., Tijerina-Chávez, L., Govaerts, B., 2011b. Soil quality as affected by tillage-residue management in a wheat-maize irrigated bed planting system. Plant Soil 340, 453–466.

Walkley, A., Black, J.A., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37. 29–38.

Weil, R.R., Magdoff, F. 2004. Significance of soil organic matter to soil quality and health. In: Magdoff, F., Weil, R.R. (Eds), Soil Organic Matter in Sustainable Agriculture, CRC Press: Boca Raton, FL, USA, pp 1-43.

Wu, L., Wood, Y., Jiang, P., Li, L., Pan, G., Lu, J., Chang, A.C., Enloe, H. A., 2008. Carbon sequestration and dynamics of two irrigated agricultural soils in California. Soil Sci. Soc. Amer. J., 72, 808-814.

Figure captions

Fig 1. Monthly cumulative precipitation (rainfall and irrigation) and average maximum and minimum temperature from September 2009 to September 2012 at the experimental site in Córdoba (Spain).

Fig. 2. Scheme of planting systems (PB, permanent bed planting; DPB, decompacted permanent planting; CB, conventional planting) and furrows with traffic (+T) and without traffic (−T) in one block. Vertical arrows indicate decompacted furrows.

Fig. 3. Soil cone index in the permanent (PB), decompacted permanent (DPB; italic) and conventional (CB; bold) bed planting systems in bed, shoulder (S) and furrow (F) sites, with (+T) and without (-T) traffic, in November 2012. SWC (%) indicates volumetric soil water content (0-0.6 m layer) by planting in beds and furrows. Asterisks and different letters within the same depth and position indicate significant differences at $p < 0.05$.

Fig. 4. Root length density (cm cm^{-3}) in soil layers 0-0.6 m (a) and 0.6-1.0 m (b) in the permanent (PB), decompacted permanent (DPB) and conventional (CB) bed planting systems. Positions 0,4 and -4 correspond to plant row, and centre of furrows with and without traffic, respectively. Other positions are intermediate. For each soil layer and planting system, positions with different lower case letters differ at $p < 0.05$; for each soil layer and position, planting systems with different upper case letters differ at $p < 0.05$ when indicated.

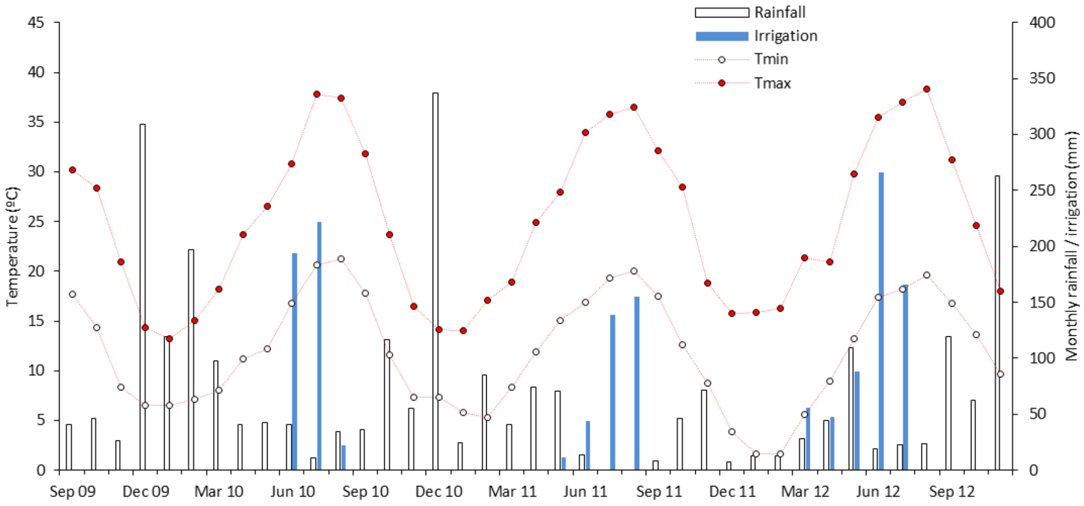
Fig. 5. Crop residues (Mg ha^{-1}) on beds and furrows with (F+T) and without traffic (F-T) in the permanent planting system. Data from 2008 to 2010 are adapted from Boulal et al. (2012) and Panettieri et al. (2013). Bars indicate half standard deviation. Asterisks indicate significant differences between positions on each sampling date at $p < 0.05$. Values in F+T furrows in decompacted permanent (DPB) planting system are also shown (not included

in means comparisons). Dashed and dashed-dotted lines indicate cotton and maize seasons; crosses mark dates of stalks slashing. Vertical arrows indicate subsoiling in DPB.

Fig. 6 Crop residue biomass (Mg ha^{-1}) and soil area covered by the biomass (%) in (a) autumn and (b) spring samplings. Different symbols indicate different sampling dates. Data from 2008 to 2010 have been adapted from Boulal et al. (2012) and Panettieri et al. (2013).

Fig. 7. Soil organic carbon concentration (SOC, %) in top 0.05-m soil layer in beds and furrows with traffic (F+T) in the permanent (PB), decompacted permanent (DPB) and conventional (CB) bed planting systems from 2007 to 2012. Values from 2007 to 2009 were taken from Boulal et al. (2012). Bars are half standard deviations. Dashed and solid lines indicate growing seasons for cotton and maize.

Fig. 8. Soil organic carbon stock (SOCs, Mg ha^{-1}) in 0-0.3, 0-0.5 and 0-1 m layers in the permanent (PB) and conventional (CB) bed planting systems at the end of the study (November 2012). Bars indicate standard deviation. Different letters within the same soil layer indicate significant differences between planting systems at $p < 0.05$.



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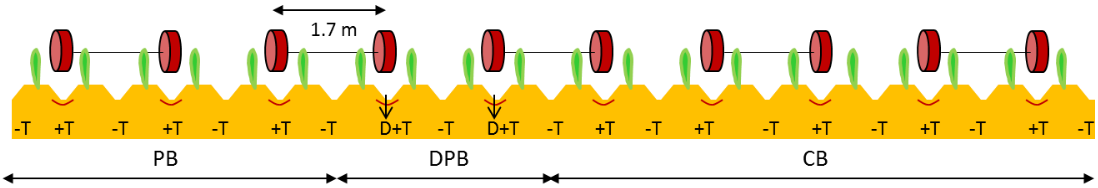

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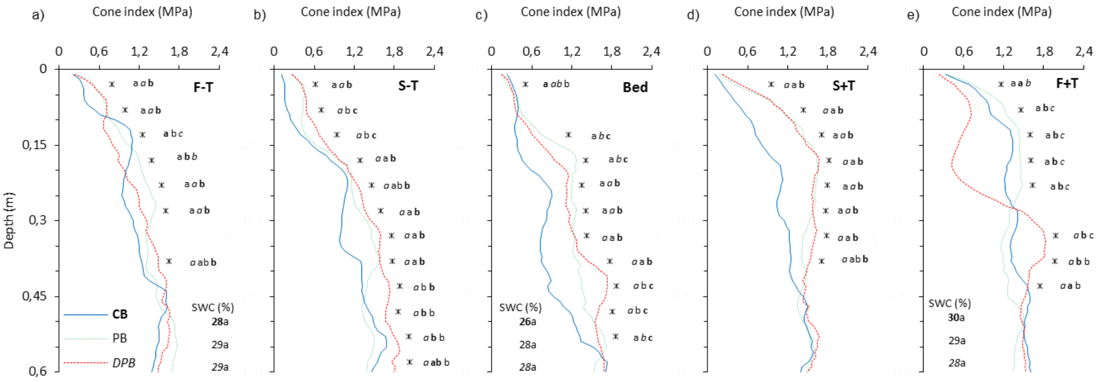

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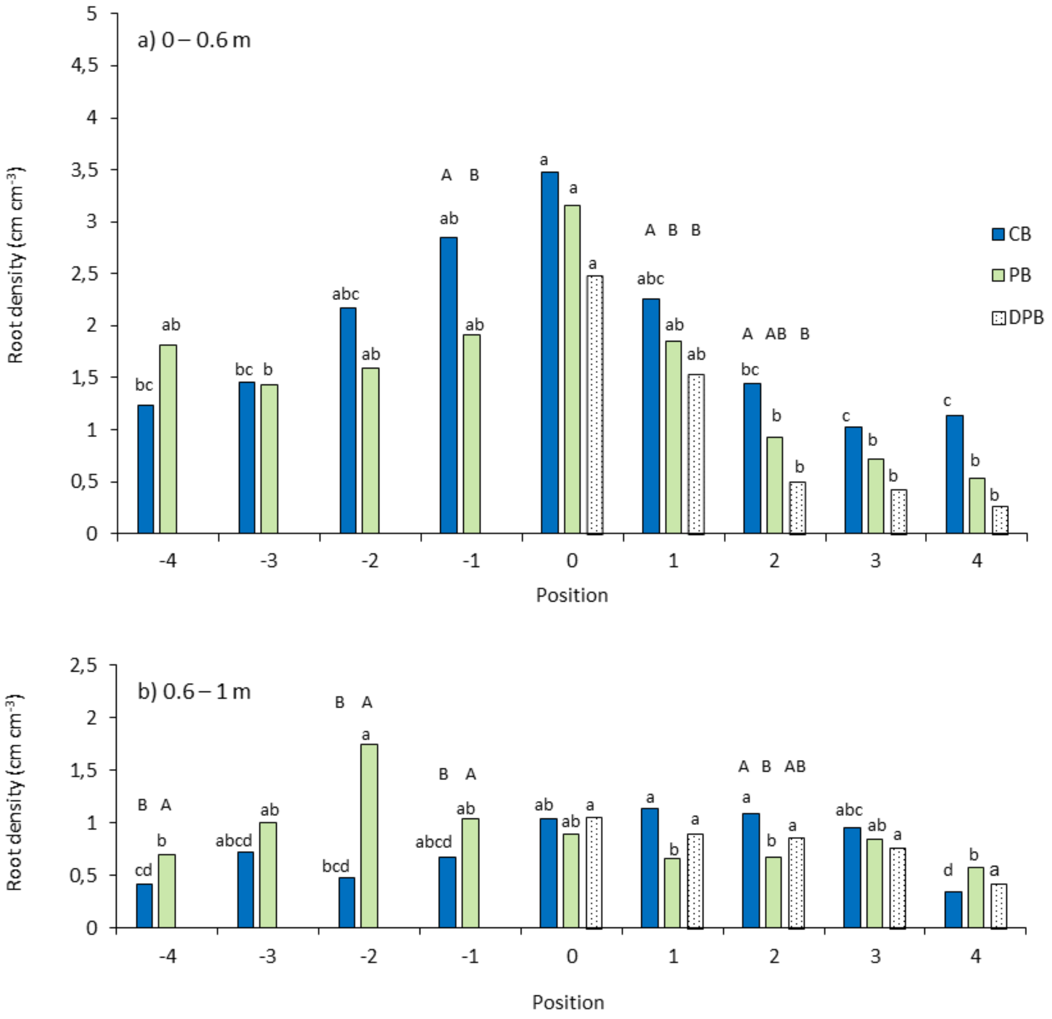

Fig. 4. Root length density (cm cm^{-3}) in soil layers 0-0.6 m (a) and 0.6-1.0 m (b) in the permanent (PB), decompacted permanent (DPB) and conventional (CB) bed planting systems. Positions 0,4 and -4 correspond to plant row, and centre of furrows with and without traffic, respectively. Other positions are intermediate. For each soil layer and planting system, positions with different lower case letters differ at $p < 0.05$; for each soil layer and position, planting systems with different upper case letters differ at $p < 0.05$ when indicated.

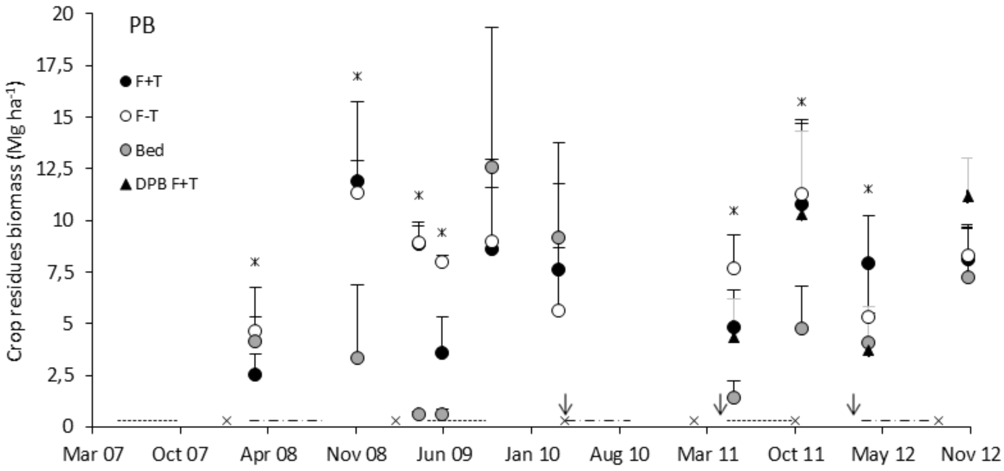

Fig. 5. Crop residues (Mg ha^{-1}) on beds and furrows with (F+T) and without traffic (F-T) in the permanent planting system. Data from 2008 to 2010 are adapted from Boulal et al. (2012) and Panettieri et al. (2013). Bars indicate half standard deviation. Asterisks indicate significant differences between positions on each sampling date at $p < 0.05$. Values in F+T furrows in decompacted permanent (DPB) planting system are also shown (not included in means comparisons). Dashed and dashed-dotted lines indicate cotton and maize seasons; crosses mark dates of stalks slashing. Vertical arrows indicate subsoiling in DPB.

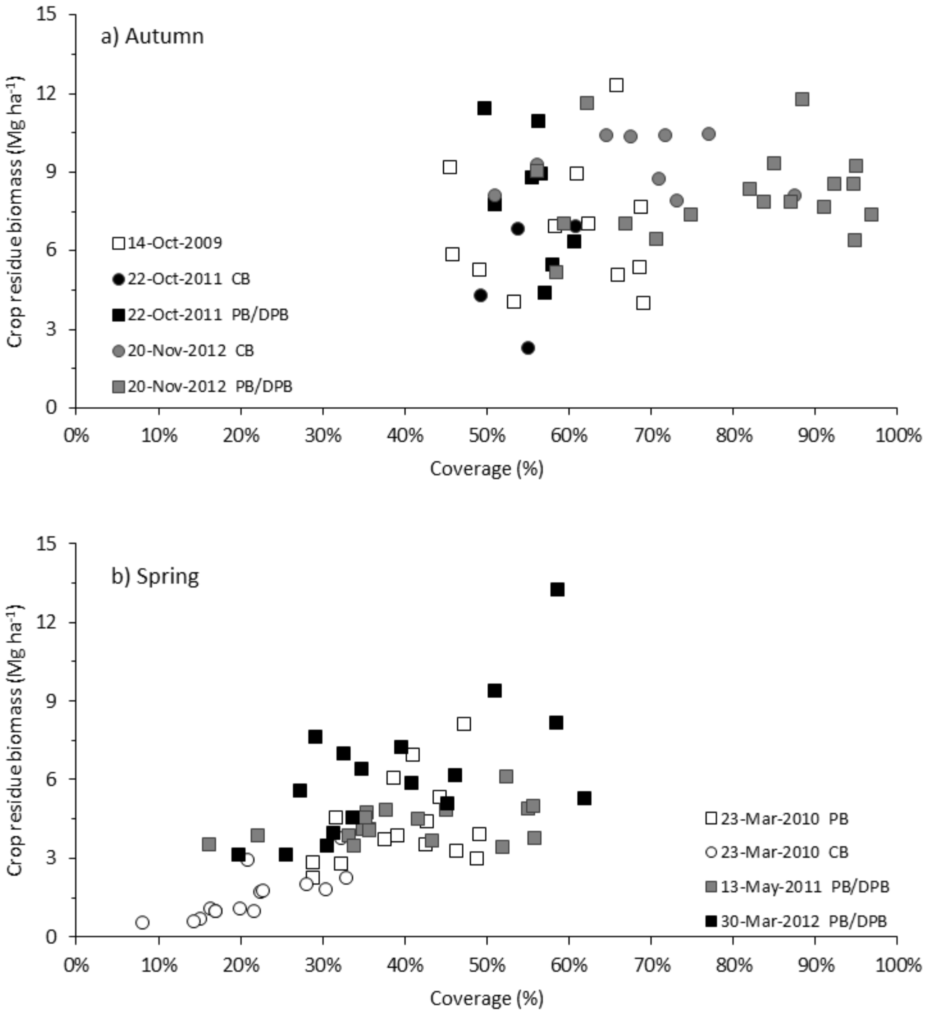

Fig. 6 Crop residue biomass (Mg ha^{-1}) and soil area covered by the biomass (%) in (a) autumn and (b) spring samplings. Different symbols indicate different sampling dates. Data from 2008 to 2010 have been adapted from Boulal et al. (2012) and Panettieri et al. (2013).

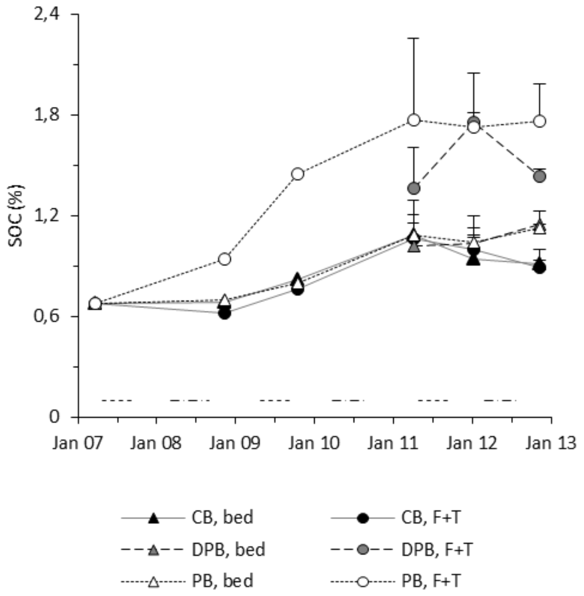

Fig. 7. Soil organic carbon concentration (SOC, %) in top 0.05-m soil layer in beds and furrows with traffic (F+T) in the permanent (PB), decompacted permanent (DPB) and conventional (CB) bed planting systems from 2007 to 2012. Values from 2007 to 2009 were taken from Boulal et al. (2012). Bars are half standard deviations. Dashed and solid lines indicate growing seasons for cotton and maize.

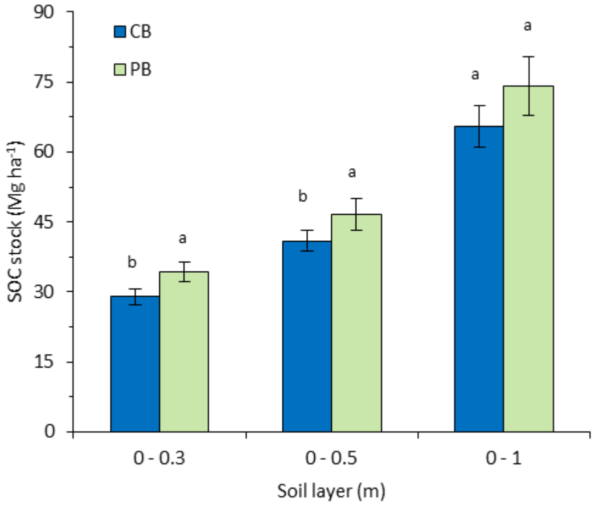

Fig. 8. Soil organic carbon stock (SOCs, Mg ha^{-1}) in 0-0.3, 0-0.5 and 0-1 m layers in the permanent (PB) and conventional (CB) bed planting systems at the end of the study (November 2012). Bars indicate standard deviation. Different letters within the same soil layer indicate significant differences between planting systems at $p < 0.05$.

Table 1. Farming operations performed at the experimental plot during the study (ASABE Standards, 2005).

Date	Operation	System
9-Nov-09	Herbicide application: Glyphosate 36%, 7.5 L ha^{-1}	all
6-Apr-10	Cotton residues slashing. Herbicide: Glyphosate 36%, 6 L ha^{-1} + Oxifluorfen 48%, 2 L ha^{-1}	all
7-Apr-10	Subsoiling to 0.55 m, three legs 0.675 m apart	CB
8-Apr-10	Subsoiling in F+T to 0.35 m, two legs 1.7 m apart	DPB
	Disc plow (0.2 m); harrowing (0.25 m); bedding (0.85m bed spacing)	CB
10-Apr-10	**Maize cv. *Sancia* sowing**, 120000 seeds ha^{-1}; insecticide: Chlorpyrifos 5%, 4.6 kg ha^{-1}	all
12-Apr-10	Fertilization: NPK(S) 15-15-15-(15), 750 kg ha^{-1}	all
7-May-10	Herbicide: Terbuthylazine 50%, 1.9 L ha^{-1} + Fluroxypir 20%, 1 L ha^{-1}	all
10-May-10	Fertilization: urea 46% N, 350 kg ha^{-1}	all
26-May-10	Insecticides: Chlorpyrifos-Methyl 22.4%, 2 L ha^{-1} + Abamectin 1.8%, 1 L ha^{-1}	all
26-Sep-10	Maize harvest	all
9-Feb-11	Residues processing: slashing of standing maize residues	all
7-Apr-11	Herbicide: Glyphosate 36%, 7.5 L ha^{-1}	all
13-Apr-11	Subsoiling in F+T (0.35 m)	DPB
27-Apr-11	Subsoiling (0.55 m); disc plow (0.2 m), harrowing (0.25 m); bedding	CB
11-May-11	**Cotton cv. *Coko* sowing**, 300000 seeds ha^{-1}; insecticide: Chlorpyrifos 5%, 5 kg ha^{-1}	all
13-May-11	Herbicide: Fluometuron 50%, 3.1 L ha^{-1} + Glyphosate 36%, 3.8 L ha^{-1}	all
23-Jun-11	Inter row cultivation (0.05-0.1m)	CB
28-Jun-11	Fertilization: urea 46% N, 150 kg ha^{-1}	all
7-Jul-11	Insecticide: Thiacloprid 48%, 0.2 L ha^{-1}	all
12-Jul-11	Fertilization: urea 46% N, 150 kg ha^{-1}	all
29-Sep-11	Cotton harvest	all
18-Oct-11	Residues processing: slashing of standing cotton residues	all
19-Jan-12	Herbicide: Glyphosate 36%, 6 L ha^{-1} + Oxifluorfen 48%, 2 L ha^{-1}	all
23-Feb-12	Subsoiling (0.5 m); disc plow (0.2 m), harrowing (0.25 m); bedding	all
7-Mar-12	Subsoiling in F+T (0.35 m)	DPB
13-Mar-12	Herbicide: Terbuthylazine 21.4%, 2.5 L ha^{-1} + Acetochlor 45%, 2.5 L ha^{-1}	all
14-Mar-12	**Maize cv. *Sancia* sowing**, 90000 seeds ha^{-1}; insecticide: Chlorpyrifos 5%, 8 kg ha^{-1}	all
27-Mar-12	Fertilization NPK(S): 15-15-15-(15), 750 kg ha^{-1}	all
12-Apr-12	Fertilization: urea 46% N, 150 kg ha^{-1}	all
26-Apr-12	Herbicide: Terbuthylazine 50%, 2.5 L ha^{-1} + Fluroxypir 20%, 0.6 L ha^{-1}	all
27-Apr-12	Insecticide: Chlorpyrifos-Methyl 22.4%, 0.6 L ha^{-1} + Abamectin 1.8%, 1 L ha^{-1}	all
16-May-12	Fertilization: urea 46% N, 175 kg ha^{-1}	all
22-Aug-12	Maize harvest	all
13-Sep-12	Residues processing: slashing of standing maize residues	all

Table 2. Grain or seed yield, above ground dry weight (AGDW), number of plants per unit area (# plants m^{-2}), number of ears per plant (#ears plant^{-1}), grain weight per ear, 1000 kernels weight (1000 kn wt), number of open bolls per plant (#bolls plant^{-1}), seed+lint weight per boll and plant height at maturity of maize (2010, 2012) and cotton (2011) in the permanent (PB), decompacted permanent (DPB) and conventional (CB) bed planting systems.

Maize		# plants m^{-2}	# ears plant^{-1}	grain wt ear^{-1} (g)	1000 kn wt (g)	Grain yield (g m^{-2})	AGDW (g m^{-2})	Plant height (m)
2010	PB	9.6 ± 1.0 ab	0.9 ± 0.1 a	132 ± 31.6 b	286 ± 21 b	1042 ± 250 b	1965 ± 449b	2.5 ± 0.2 b
	DPB	8.9 ± 1.4 b	0.9 ± 0.0 a	156 ± 24.1 a	304 ± 25 a	1249 ± 152 a	2218 ± 260a	2.6 ± 0.1 b
	CB	10.5 ± 0.9 a	0.9 ± 0.1 a	157 ± 21.4 a	290 ± 18 ab	1527 ± 115 a	2663 ± 195a	2.7 ± 0.1 a
2012	PB	7.8 ± 1.0 a	1.0 ± 0.0 a	194 ± 30.7 a	305 ± 39 a	1243 ± 212 a	2715 ± 380a	2.8 ± 0.1 ab
	DPB	8.3 ± 0.8 a	1.0 ± 0.0 a	200 ± 34.8 a	318 ± 39 a	1426 ± 232 a	2912 ± 450a	2.9 ± 0.1 a
	CB	8.1 ± 0.5 a	1.0 ± 0.0 a	197 ± 36.0 a	310 ± 42 a	1272 ± 220 a	2592 ± 438a	2.7 ± 0.1 b

Cotton		# plants m^{-2}	# bolls plant^{-1}	seed+lint weight ball^{-1} (g)		Seed+lint yield (g m^{-2})	AGDW (g m^{-2})
2011	PB	10.8 ± 2.9 a	4.3 ± 1.7 a	4.4 ± 0.8 a		185 ± 33 a	503 ± 90ab
	DPB	11.2 ± 2.7 a	4.3 ± 1.1 a	4.4 ± 0.7 a		208 ± 55 a	569 ± 148a
	CB	11.2 ± 2.9 a	3.9 ± 1.8 a	4.5 ± 1.0 a	-	176 ± 45 a	439 ± 101b