Tesis doctoral

AGRICULTURA DE CONSERVACIÓN EN LOMOS PERMANENTES BAJO RIEGO Y COMPACTACIÓN: EFECTOS EN EL AMBIENTE EDÁFICO Y EL DESARROLLO DEL CULTIVO

CONSERVATION AGRICULTURE IN IRRIGATED PERMANENT BEDS AND SOIL COMPACTION: EFFECTS ON THE EDAPHIC ENVIRONMENT AND CROP GROWTH AND DEVELOPMENT

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Bajo la dirección de la Doctora Helena Gómez Macpherson

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Agricultura de conservación en lomos permanentes bajo riego y compactación: efectos en el ambiente edáfico y el desarrollo del cultivo

DOCTORANDO/A:

Patricio Cid

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

La Tesis del doctorando se ha centrado en el estudio de un sistema agrícola prácticamente inexistente en Andalucía pero que, según los pocos ejemplos disponibles, tiene un potencial notable para la conservación de suelo y agua y para el secuestro de carbono. Además, la evaluación del sistema en estos términos requiere la consideración de variaciones espaciales y temporales y de escala. El doctorando comenzó por tanto con una revisión exhaustiva de estudios sobre agricultura de conservación en sistemas de cultivos anuales regados y sobre la compactación del suelo agrícola. Enseguida comenzó su participación intensa en un ensayo de larga duración, sito en el campus Alameda del Obispo, cuyos resultados corresponden al cuerpo central de su trabajo. El doctorando estudió el sistema globalmente en términos de crecimiento, rendimiento y eficiencia del agua a la vez que profundizó en la variabilidad espacial y temporal, particularmente en el suelo. En su tercer año, y para evaluación del sistema en términos de conservación de suelo, el doctorando trabajó con datos tomados en una cuenca cuyo análisis le requirió gran minuciosidad. El trabajo del doctorando se completa con una estancia de 6 meses en el Departamento de Suelos y Cultivos de la Universidad del Estado de Colorado.

El formato de la tesis es clásico y se presenta por capítulos de los que uno corresponde a un artículo SCI ya publicado.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 16 de octubre de 2013

Firma de la directora

Fdo.:__________________

Comentarios y agradecimientos

Entre Julio de 2009 y Junio de 2013 disfruté de una beca predoctoral JAE Predoc del Consejo Superior de Investigaciones Científicas (CSIC) para realizar mi trabajo de tesis doctoral en el Instituto de Agricultura Sostenible-CSIC, en la ciudad de Córdoba, España.

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Summary

Agriculture is a case of soil-biology-atmosphere interaction from which the environment can be positively or negatively affected depending on the use of the factors involved. Annual crop based systems managed conventionally, i.e. crop residues are burned and/or mouldboard plough is used combined with secondary tillage, expose the soil to the effect of rain and runoff that may imply, ultimately, soil erosion. Since conservation agriculture (CA) implies reduced or zero tillage plus maintenance of plant residues and crops rotation, this type of agriculture is commonly seen as a way of producing food and fibre while minimizing environmental risks.

Irrigated permanent beds combined with controlled traffic (PB) is a form of CA that, in the short term, improves soil organic matter (SOM) and reduce soil erosion risk relative to conventionally tilled beds also combined with controlled traffic (CB) without apparent limitations for crop growth. However, viable agricultural systems have to be productive and efficient beyond the short term, and PB system was tested on the medium term in both experimental plots and commercial plots in the province of Córdoba in terms of soil quality, use of water by crop, crop growth and yield, hydrological behaviour at catchment scale and erosion risk. The study was completed with a third planting system (DPB) established in part of PB in the experimental plot by carrying out a decompacting subsoiling operation at the start of each cropping season.

CB, PB and DPB were evaluated in terms of soil conditions and crop growth (both above as below ground) and yield from 2010 to 2012, i.e. from the fourth to the sixth year since the establishment of the experiment. Controlled traffic and tillage resulted in spatial variation of soil properties. During the period considered, soil was more compacted in PB than in CB and in furrows than in beds. Subsoiling in trafficked furrows in DPB resulted in lower compaction than in equivalent furrows in PB. In spite of differences in compaction among planting treatments, no clear tendencies were observed in terms of crop above ground biomass production and yield throughout the three years. On the contrary, root system development differed spatially and among planting systems. More roots were developed in shallow soil (0.0-0.6 m top soil layer) in CB and in deeper soil (0.6-1.0 m soil layer) in PB. DPB had the lowest root density because subsoiling created a hard pan just under its working depth. In all planting systems, traffic influenced root growth, which concentrated in sites free of tractor-wheel influence.

Crop residues, an important component of the PB and DPB systems, accumulated mainly in furrows compared with beds. Higher accumulation of residues and soil moisture in PB furrows resulted in higher SOC concentration in the top 0.05 m layer than in beds: 1.67 vs.

1.09%, respectively. Soil ridging to prepare beds promoted CO2 emissions from beds in CB and vertical-zone tillage increased emissions in furrows in DPB, resulting in reduced SOC. In DPB, SOC in F+T the 0.05 m top layer was 1.52% on average. In CB, SOC in the top 0.05 m increased to reach 0.96% on average.

The absence of soil tillage in PB resulted in higher superficial SOC compared to CB but no significant differences were observed in deeper layers. On the contrary, SOC storage was 5.7 Mg ha^{-1} significantly higher in PB compared with CB for 0.5 m top soil layer. The difference for the full 1-m studied profile (8.7 Mg ha^{-1} more carbon in PB than CB) was not significant. An evaluation of PB and other irrigated systems under CA should be evaluated at regional level to estimate their potential contribution for C sequestration.

Water cycle and erosion were assessed in an irrigated annual crops based-catchment in a commercial farm where semipermanent bed planting (three years cycle), zone vertical-tillage and crop rotations are used. A hydrological station located at the outlet of a catchment of 27 ha was used to monitor runoff and sediment concentration during irrigation and rainfall events. Mean annual runoff coefficient was 0.14 and mean annual soil loss was 2.4 Mg ha^{-1} year^{-1}. Irrigation contributed with 40% of the crop water supply but the amount of runoff and sediment yield that it generated was negligible. The main factors determining runoff and sediment losses were soil moisture and crop residues covering the soil surface at the time of each runoff event. Some agrochemicals were also exported with runoff water, something that must be evaluated in more depth.

On the whole, permanent bed planting, as a variant form of conservation agriculture systems, produce goods in the Mediterranean environment while offering some externalities such as improvement in soil quality, enhancement in carbon sequestration and reduction in erosion risk.

Resumen

La agricultura es un caso de interacción suelo-biología-atmósfera a partir del cual el medio ambiente puede ser afectado positiva o negativamente dependiendo del modo en que se utilicen los factores que intervienen. Sistemas agrícolas basados en cultivos anuales manejadas convencionalmente, es decir, con quema de rastrojos y/o utilización de arados de reja y vertedera combinados con labranzas secundarias, exponen el suelo al efecto de la lluvia y de la escorrentía, llevando en última instancia a la erosión del suelo. Dado que la agricultura de conservación (AC) implica uso reducido o ausencia de labranzas, permanencia de rastrojos y rotación de cultivos, su implementación es comúnmente vista como una forma de producir alimentos y fibras reduciendo al mínimo los riesgos ambientales.

Las camas permanentes con riego y tráfico controlado (CP) son una forma de AC que, en el corto plazo, aumenta la materia orgánica del suelo (MOS) y reduce el riesgo de erosión en comparación con sistemas de camas con labranza convencional también combinados con tráfico controlado (CC) sin limitaciones aparentes para el crecimiento de los cultivos. Sin embargo, los sistemas agrícolas viables tienen que ser productivos y eficientes más allá del corto plazo, por lo cual el sistema CP fue evaluado en el mediano plazo en términos de la calidad del suelo, crecimiento, rendimiento del cultivo, uso de agua, comportamiento hidrológico a escala de cuenca y el riesgo de erosión, tanto en parcelas experimentales como en parcelas comerciales en la provincia de Córdoba. El estudio se completó con un tercer sistema de siembra (CPD), creada en parte del sistema CP en la parcela experimental mediante la realización de una operación de subsolado y descompactación al inicio de cada temporada de cultivo.

CC, CP y CPD se evaluaron en cuanto a condiciones de suelo, el crecimiento de los cultivos (tanto por encima como por debajo del suelo) y su rendimiento desde 2010 a 2012, es decir, desde el cuarto hasta el sexto año desde el establecimiento del estudio. El tráfico controlado y labranza produjeron variación espacial de las propiedades del suelo. Durante el período considerado, el suelo en CP estaba más compactado que en CC fundamentalmente en los surcos. El subsolado en surcos con tráfico en CPD resultó en una menor compactación que en surcos equivalente en CP. A pesar de las diferencias de compactación entre los sistemas de cultivo, no se observaron tendencias claras en términos de rendimiento o de producción de biomasa del suelo y el rendimiento a lo largo de los tres años. Por el contrario, el desarrollo del sistema radicular si difirió espacialmente y entre sistemas de cultivo. Un mayor número de raíces se desarrollaron en suelo poco profundo (0.0-0.6 m) en el sistema CC y en el suelo profundo (0.6-1.0 m) en CP. CPD presentó la menor densidad de raíces porque subsolado creó una capa de suelo

compactada justo por debajo de la profundidad de trabajo. En todos los sistemas de cultivo el tráfico tuvo influencia sobre el crecimiento de las raíces, que se concentraron en los sitios libres de la influencia de las ruedas del tractor.

Los residuos de cultivos, un componente importante de los sistemas de CP y CPD, se acumularon principalmente en los surcos. La mayor acumulación de residuos y la humedad del suelo en surcos del sistema CP dieron como resultado una concentración más alta del carbono orgánico de suelo (COS) en los primeros 0.05 m de suelo de aquellos en comparación con las camas: 1.67 vs. 1.09%, respectivamente. El alomado de suelo para preparar las camas promovió emisiones de CO2 desde las camas en CP y la labranza vertical localizada aumentó las emisiones en surcos con tráfico de CPD, lo que resultó en una reducción de COS. En CPD, el COS de los primeros 0.05 m de suelo en los surcos con tráfico fue 1.52% en promedio. En CC, COS en los 0.05 m superiores aumentó hasta alcanzar el 0.96% en promedio.

La ausencia de labranza del suelo en CP resultó en mayor COS superficial en comparación con CC pero no se observaron diferencias significativas en las capas de suelo más profundas. Por el contrario, el almacenamiento de COS fue 5.7 Mg ha^{-1}, mayor en CP que en CC (siendo las diferencias estadísticamente significativas) dentro de los primeros 0.5 m de suelo. La diferencia para el completo todo el perfil de suelo estudiado (8.7 Mg ha^{-1} más carbono en CP que en CC en el primero metro de profundidad) no fue significativa. Los sistemas CP junto a otros sistemas de AC con riego necesitan ser evaluado a nivel regional para estimar su contribución potencial para la captura de carbono en el suelo.

El ciclo del agua y la erosión fueron evaluados en una cuenca con cultivos anuales regados ubicada dentro de una finca comercial en la que se utiliza un sistema de siembra en camas semipermanente (con un ciclo de tres años), labranza vertical localizada y rotaciones de cultivo. Una estación hidrológica que se encuentra a la salida de una cuenca de 27 ha fue utiliza para medir la escorrentía y la concentración de sedimentos durante eventos de escorrentía ocasionados por lluvias y riego. El coeficiente medio anual de escorrentía fue de 0.14 y la media de pérdida anual de suelo fue de 2.4 Mg ha^{-1} año^{-1}. El riego contribuyó con 40% del suministro de agua del cultivo, aunque la cantidad de escorrentía que aquel ocasionó y los sedimentos arrastrados fueron insignificantes. Los principales factores que determinaron la escorrentía y la pérdida de sedimento fueron la humedad del suelo y la presencia de rastrojos cubriendo la superficie del suelo al momento de ocurrir cada evento. Algunos productos agroquímicos también se exportaron con el agua de escorrentía, algo que debe ser evaluado con mayor profundidad.

En general, la siembra en camas permanentes, como una variante de los sistemas de agricultura de conservación, produce bienes en el entorno mediterráneo mientras que ofrece ciertas externalidades como la mejora en la calidad del suelo, la acumulación de carbono y la reducción del riesgo de erosión.

Chapter 1 - General Introduction

1.1. Agriculture and sustainability

Agriculture is an economic activity where soil, biology and atmosphere interact to obtain goods such as food, fibre and fuel. Depending on the level of pressure exerted by any agriculture activity on natural resources, the surrounding environment can be harmed or benefited. An understanding of the interactions is then necessary for improving the efficiency of used resources as well as for minimizing social and ecosystem risks.

The introduction of new crops and varieties, the use of new machinery and technologies, the uncertainties regarding oil availability and input and output prices, together with increasing concern on environmental issues by the society, put agriculture under a continuous challenge: to produce more and better goods while doing it more efficiently than before and, at the same time, to offer positive externalities like carbon sequestration (Lal, 2010) and enhancement of the landscape (Gómez-Limón and Riesgo, 2010), among others. This challenge requires the development and adoption of new technology and farming practices while pursuing sustainability targets (Table 1). The ultimate goal of agricultural sustainability is to ensure the resources required for maintaining or improving systems productivity for future generations. This will only occur if farm net profit is sufficient for a respectable life.

In Mediterranean regions, characterized by recurrent droughts and high atmospheric water demand concentrated in summer, irrigation is imperative for intensifying agriculture systems (Caraveli, 2000). In Spain, 7% of winter cereals, 10% of legumes, 10% of sunflower (*Helianthus annuus* L.), 93% of maize (*Zea mays* L.) and 93% of cotton (*Gossypium hirsutum* L.) cultivated surface are conducted under irrigation, these areas contribute with 11%, 17%, 16%, 95%, 97%, respectively, to the total national production (MAGRAMA, 2013). In Andalusia, the area of irrigated annual crop-based systems was 280,000 ha in 2010, 16% of the national irrigated area with annual crops, being rice, cotton and maize the main irrigated spring crops in terms of extension (43% of the irrigated surface) (MAGRAMA, 2012).

Irrigation has an important role in agricultural sustainability because of its higher potential for increasing global food production (Parry *et al.*, 2005; Schmidhuber and Tubiello, 2007) and for maintaining biodiversity. Regarding the latter, the range of grown crops in a certain region and farm widens with irrigation, increasing the chances of crops rotations and diversifying the rural landscape (Gómez-Limón *et al.*, 2007). However, this intensification is more demanding on the farmer than rainfed systems (Naor, 2006).

Irrigation is usually accompanied by an increase of inputs use, e.g. fertilizers or pesticides, which contribute to the intensification of the system (Caraveli, 2000). The introduction of irrigation in an agriculture system may also increase the risk of soil erosion (Carter, 1990; Fernández-Gómez *et al.*, 2004) and watersheds contamination (Isidoro *et al.*, 2006; Johannsen and Armitage, 2010; García-Garizábal *et al.*, 2012). Therefore, irrigated systems require, a close monitoring of soil erosion and contaminants at both plot and watershed scales.

Loss of soil and nutrients, degradation of the landscape and pollution of streams with sediments and agrochemicals, may be concomitant during the process of erosion (Pimentel *et al.*, 1995). In the particular case of annual-based cropping systems in southern Spain, risk of soil erosion is higher when the conventional practices, e.g. ploughing for soil preparation, leave the soil ground with no protection from water drops impacts and runoff. Soil tillage, particularly with soil inversion, also increases the exposure of soil organic matter (SOM) to microorganisms accelerating its biodegradation and, in turn, decrease soil structure stability leading to further increase in risk of soil erosion (Bronick and Lal, 2005).

Table 1. Sustainability targets for agriculture

Impacts	Targets
Overall	Maintain/improve productivity for future generations
Economic	Optimise farm productivity
	Maintain contribution to the wider economy
Environmental	Preserve and protect natural water resource
	Improve soil health
	Minimise adverse effects on water source and receiving waters
	Minimise adverse effects on air
	Maintain or enhance biodiversity, habitats, and landscape
	Pursue effective waste management
	Minimise use of non-renewable energy resources
Social	Ensure acceptability of farming practices to the wider community
	Demonstrate good environmental management on the market scale

Adapted from García-Tejero *et al.* (2011)

1.2. Conservation agriculture

The lack of sustainability of conventional farming systems concerning soil erosion and poor fertility has driven the development of conservation agriculture (CA) (Hobbs *et al.*, 2008). CA, based on minimum soil disturbance (reduced or no-tillage), maintenance of crop residues covering the soil surface and crop rotation (FAO, 2012), use the production factors in such a manner that the systems and the environment are expected to be improved. Described direct benefits include: labour and fuel savings, interception of radiation by the crop residues and reduction in available energy for soil water evaporation, increase in soil protection against water drops detachment effect and erosion, and possibility of crop intensification with the reduction in time requirement for soil preparation (Baker and Saxton, 2007; Verhulst *et al.*, 2010; Hatfield *et al.*, 2001; Tolk *et al.*, 1999; Morell *et al.*, 2011; Wang *et al.*, 2011). In the long term, reduced tillage plus maintenance of crop residues generally increase soil organic carbon (SOC) in the shallowest soil layer, improve soil structure by promoting aggregates formation and stabilization, foster soil water infiltration and reduce runoff and soil erosion risk, increase soil water storage and enhance biodiversity (Govaerts *et al.*, 2009). Crop rotations are important in a CA system for facilitating weed control, for reducing pests pressure, and for enhancing soil biota like earthworms, which in turn may alleviate compaction and improve soil aeration (House and Parmelee, 1985; Andow, 1991; Liebman and Dyck, 1993; Lupwayi *et al.*, 1998; Brévault *et al.*, 2007; Errouissi *et al.*, 2011).

Despite these claimed benefits, the cultivated area under CA in Spain, as in the entire Europe, is extremely low (Table 2). The poor adoption applies to every Mediterranean climate country (Friedrich *et al.*, 2012), except for Australia, and figures are even lower under irrigated agriculture (Gómez-Macpherson *et al.*, 2009). Spanish national statistics indicate that 510,000 ha across Spain were directly sown annual crops (cereals, sunflower and forage crops) in 2011, from which 73,000 ha corresponded to Andalusia (MAGRAMA, 2012, 2013). However, no information is provided regarding crop residues management and crop rotations (or if rotated crops are also no-tilled), hence it is not possible to confirm if the declared surface comply the three principles of CA. In perennial crops, soil conservation techniques has spread significantly in olive orchards in Andalusia by using no- or minimum-tillage and cover crops, particularly under irrigation (MAGRAMA, 2012, 2013).

Table 2. Area with conservation agriculture (CA) in Spain and in some countries where its use is widespread. In each case, the most recent figure is shown and the year is indicated between parentheses.

Country	CA area as % of cultivated area	CA area (1000 ha)	
Argentina	65.4%	25553	(2009)
Uruguay	35.5%	655	(2008)
Australia	35%	17000	(2008)
Canada	35%	16590	(2011)
Brazil	34%	25502	(2006)
USA	16%	26500	(2007)
Spain	4%	650	(2008)
Europe*	2%	6354	(2008-11)

(*) Finland, France, Germany, Netherlands, Portugal, Republic of Moldova, Russian Federation, Spain, Switzerland, Ukraine, United Kingdom.
Source: FAO (2013).

Friedrich *et al.* (2012) indicate that, in the European Union, policies of subsidies and direct payments to farmers represent some of the barriers to adoption of CA. Other possible reason that impedes CA diffusion is the different elapsed times to face challenging situations or to achieve benefits after adoption (Soane *et al.*, 2012). On the one hand, some years and cropping seasons are required to achieve significant increases in SOM (Ordóñez-Fernández *et al.*, 2007; Govaerts *et al.*, 2009) or to make available nutrients immobilized in crop residues accumulated on soil surface (Martens 2001; Verhulst et al. 2010) in systems converted from conventional to conservation tillage. On the other hand, soil compaction and problems associated with weed control or the accumulation of crop residues on the soil surface appear soon after adoption of CA. In conventional agricultural systems, crop residues are baled, burned or buried by soil tillage during soil preparation for sowing. Thus, when switching from conventional to CA systems crop residues become a new element which farmers have to deal with.

1.3. Soil compaction

Soil compaction is the process by which the volume occupied by a given mass of soil is reduced or, what is the same, the pore volume is reduced. During the compaction process, the highest breakdown of pore space occurs within the volume corresponding to macropores (Soane *et al.*, 1980a; Bullock *et al.*, 1985), i.e. pores greater than 60 μm in diameter (Porta *et al.*, 1999). Together with the reduction in diameter, compaction also decreases continuity of pores (Soane *et al.*, 1980a) and air entrance and movement in the profile (diffusivity and permeability) (Ball and Robertson, 1994), which reduces the volume of air available for any soil organism and plant roots. For example, in compacted soils compared to tilled soils, low oxygen supply may reduce earthworms number (Whalley *et al.*, 1995) and roots growth (Taylor and Brar, 1991).

In agriculture, some soil compaction may be desirable to offer appropriate root anchorage (Taylor and Gardner, 1960a), to facilitate the transport of water in furrow irrigation (Carter, 1990), to provide adequate heat flow and promote germination (Sauer and Horton, 2005) or to improve water and nutrients uptake (Passioura, 2002). However, high level of compaction often has large negative effects on soil structure and associated soil-water–plant processes (Håkansson *et al.*, 1988).

Soil compaction is inherent in the cropping process and takes place because humans, animals and machinery transit compress soil layers in more or less degree. Machinery traffic is the main agent causing soil compaction in cropping lands. Through the wheels, the weight of agricultural machinery collapses the structure of the surface soil layers while performing farming operations. During the last decades, the trend in using larger, more powerful and heavier agricultural machinery (Soane *et al.*, 1982; Lal, 2009) had led to increasing soil compaction (both laterally and vertically) to levels not considered previously (Raper and Kirby, 2006). Furthermore, the more compacted soil is, the more powerful and heavier tractor would be required to till it (Chamen and Cavalli, 1994; Soane and van Ouwerkerk, 1995; Raper *et al.*, 2000). In the particular case of sowing, the risk of compaction is higher in CA than in conventionally tilled systems as, in the former, heavy drills that cut through crop residues and penetrate a hard seed bed are needed (Baker and Saxton, 2007).

1.3.1. Effect on below and above ground crop growth

Root systems are important for plants because they allow plant anchoring and nutrition. Additionally, roots are a major source of organic residues in soils (Kätterer *et al.*, 2011).

Inhibition of plant root growth by soil compaction has been observed in controlled conditions (Taylor and Gardner, 1963; Stirzaker *et al.*, 1996) and field experiments (Coelho et al. 2000; Busscher & Bauer 2003; Laboski et al. 1998). Soil compaction can reduce root growth and, together with this, above ground growth and / or yield, as seen in cotton (Coelho *et al.*, 2000) and maize (Chen and Weil, 2011; Tolon-Becerra *et al.*, 2011), but not necessarily an effect below ground is accompanied by an effect above ground (Busscher and Bauer, 2003; Bingham *et al.*, 2010). Root-shoot interactions can be complex and intricate. Variations in soil properties (e.g. strength, water content, nutrients, among others) may inhibit or enhance shoot growth and that, in turn, would modulate the exchange between below- and above-ground parts (Bingham, 2001; Clark *et al.*, 2003).

According to Taylor and Gardner (1963) and Taylor and Brar (1991), the soil environment can be approached as an agent that conditions root growth by means of two groups of variables: (a) '*those affecting root growth*' (aeration, humidity, fertility, pH, etc.), and (b) '*those affecting soil strength*' (bulk density, soil water content and soil strength). The former group facilitates or restricts roots cutting through soil particles as growth progresses. The second group of variables defines the mechanical limitation of the soil to be penetrated by elongating roots.

Under certain situations roots have the ability of dealing with hard soils and grow through them, but at a slower pace than in soils with optimal conditions (Taylor and Gardner, 1963; Atwell, 1993), which may be detrimental to plant to grow. However, it may occur that root apices can seize on local weaknesses that they find as they grow through the soil (Clark *et al.*, 2003). At field conditions, farm soils are highly heterogeneous and may have areas where the compaction and moisture pattern allows root growth, for example, biopores done by worms or natural cracks (Taylor and Brar, 1991; Passioura, 2002). Roots ability to find less compacted soil is supported by studies where spatial differences in soil compaction were included (Bauder *et al.*, 1985; Tardieu, 1988; Kaspar *et al.*, 1991; Coelho *et al.*, 2000; Busscher and Bauer, 2003). Additionally, different plant species have their own ability to penetrate soil (Taylor and Gardner, 1960b), still having no clear explanations for these differences.

1.3.2. Effect in water infiltration, flood and runoff

In general, compaction of soil layers reduces water infiltration and favours flooding and runoff. Flooding results in lack of oxygen for the roots, causing denitrification and plant mortality if prolonged in time (Connolly, 1998). Soil compaction increases runoff potential from a particular precipitation. Under similar weather conditions, more runoff is commonly recorded in cropping lands under reduced- or no-tillage regimes compared with cropping lands conducted under ploughing or other forms of intense tillage due to differences in soil compaction (Dos Reis Castro *et al.*, 1999; Maetens *et al.*, 2012). However, in no-tilled systems in which crop residues are maintained, the mulch created may result in increased soil water infiltration and stability of soil aggregates counteracting the negative effects originated by compaction (Karlen *et al.*, 1994; Hernanz *et al.*, 2002; Jordán *et al.*, 2010; Verhulst *et al.*, 2010).

1.3.3. Soil and crop management to deal with compaction

1.3.3.1. Controlled traffic for reducing soil compaction negative effects

Soil compaction caused with the traffic of machinery can be reduced if management is adapted to site conditions and tyre characteristics. Compaction will be deeper and higher if wheel pass takes place when soil water content is high than when soil is dry, particularly in heavy soils (Håkansson *et al.*, 1988). Regarding tyres, dual, low inflate pressure and radial-ply tyres are preferred to single, high-pressure and cross-ply tyres, respectively (Soane *et al.*, 1980b; Wood *et al.*, 1991; Botta *et al.*, 2008).

Soil compaction can be confined to zones of the field if machinery wheels traffic is always confined to transit over the same lanes, i.e. using *controlled traffic* (CT). Devices operating with Global Positioning Systems coupled to the tractor allow knowing and setting paths, recording labours details such as use of fuel among others, i.e., control the movement and performance of machinery in the field, which facilitates the adoption of CT (Chamen *et al.*, 2003; Tullberg *et al.*, 2007).

CT is justified by the high compacting potential of a single transit of wheel machinery, which makes it reasonable to concentrate traffic rather than spread it across the field (Håkansson *et al.*, 1988). The first wheel pass may compact the soil in much greater proportion compared with ulterior passes. For example, Taylor (1983) reported that 75 and 90% of total change in bulk density and sinkage, respectively, took place during the first pass within a series of four passes.

Besides confining of soil compaction, CT also reduces fuel consumption (Gasso *et al.*, 2013) and simplifies operations because farming operations are performed in a field with a systematized pattern of soil compaction, i.e., a field with areas that are completely free of traffic and areas that are compacted requires less time to complete labours and less fatigue for the operator (Baker and Saxton, 2007; Tullberg, 2010).

The spatial variation in soil compaction created with CT adoption would result in spatial variation in soil water infiltration and other soil properties (Liebig *et al.*, 1993; Boulal *et al.*, 2011b; Gasso *et al.*, 2013). In the case of irrigated systems, studies will be necessary to determine implications for irrigation management of these spatial differences (Boulal *et al.*, 2011b).

1.3.3.2. Remediating soil compaction

Soil tillage may be used to relieve compaction under conventional agricultural practices but, in general, this is not an option if CA principles are followed. Nevertheless, some authors argued that certain localized and vertical tillage operations may not significantly affect CA benefits on SOC and nitrogen accumulation (López-Fando *et al.*, 2007; López-Fando and Pardo, 2012) but may help to increase crop yield (Kirkegaard *et al.*, 2013).

Although slower in comparison with tillage, roots and soil fauna can alleviate soil compaction by creating channels or biopores (Bullock *et al.*, 1985; Clark *et al.*, 2003), further promoted by abundance of crop residues (Karlen *et al.*, 1994). In this regard, crops of the *Brassicaceae*, *Fabaceae* and *Poaceae* families with root systems capable of performing a biological drilling due to their deep and / or aggressive root systems have been studied in rotation with a main crop and proposed to undo soil compaction without using tillage (Calonego and Rosolem, 2010; Kautz *et al.*, 2010; Chen and Weil, 2011) even under CA systems (Williams and Weil, 2004). Beyond the effect on soil compaction, pores opened by biological drilling may assist and foster growth of new roots (Volkmar and Entz, 1995). However, but it should be taken into consideration that the size of pores opened by plants may result too large for an adequate root development in some cases (Cresswell and Kirkegaard, 1995; Stirzaker *et al.*, 1996). Above all, the viability of these strategies within a farming system will depends on biological and economic conditions.

1.4. Crop residues

Crop residues are important in croplands because they protect the soil surface from the impact of drops during rainfall or irrigation (Hobbs *et al.*, 2008; Durán Zuazo and Rodríguez Pleguezuelo, 2009) and, together with this, mulching slows the movement of runoff water. Growing crops themselves, by means of their canopies, protect the soil surface from rainfall drops impact; however, crop residues appear more efficient in this protective role against rain and runoff (Nearing *et al.*, 2005). Furthermore, crop residues are important before, during and after crop growing season. For example, during early crop growth or fallow periods, the presence of crop residues will offer the only protection of soil surface. This is particularly important in spring annual-based crop systems in southern Spain and other regions with Mediterranean climate where autumn and winter rainfall occurs before crop establishment.

Maintaining crop residues in the field have other benefits for the systems. Crop residues lying on soil surface reduce soil water evaporation and increase water storage for potential use by the crop (Alvarez and Steinbach, 2009; Alletto *et al.*, 2011; Soane *et al.*, 2012). Crop residues are also an important component in the dynamics of SOM. The maintenance of crop residues allows SOM accumulation in the top soil (Karlen *et al.*, 1994; Bessam and Mrabet, 2003; López-Bellido *et al.*, 2010; Melero *et al.*, 2011; De Sanctis *et al.*, 2012) provided no soil tillage incorporates crop residues and mixes soil layers. As mentioned above (Section 1.3.2), higher SOM after crop residues retention will result in enhanced structure stability and, in turns, increased water infiltration and further reduction of risk of soil erosion.

In spite of the fact that several benefits are associated with the accumulation of crop residues biomass on the cropping land, its presence represents one of the greatest challenges for crops direct-sowing. Crop residues can difficult operations that depend on machinery by hindering its operability, for example clogging the drill during sowing operation. Selecting the best drill for the local conditions is a key moment for the success of the system (Baker and Saxton, 2007). Crop residues may also slow or impede the movement of water along furrows when this irrigation method is applied (Driscoll, 2013).

The created mulch will affect the soil hydric and thermal regimes (Azooz *et al.*, 1997; Alvarez and Steinbach, 2009) and invertebrates presence (Brévault *et al.*, 2007; Errouissi *et al.*, 2011; Djigal *et al.*, 2012), among other consequences, which will have implications for management in terms of sowing dates or depths and strategies used to control of possible plagues. Crop residues interfere with the incoming solar radiation to the field resulting in lower soil heating than in a bare field. Additionally, higher soil moisture due to lower evaporation will result in even colder soil. Low soil temperatures in spring will slow down initial crop development phases (germination and emergence) increasing the risks of incidence of diseases and pests, the last also favoured by the increased moisture under the crop residues (e.g. snails, slugs, etc.). To reduce this risk, some farmers delay postharvest slashing of maize stalks until the following spring (Calleja *et al.*, 2008). Slow starting of spring crops would be translated into shortened growing season and reduced yield potential (Andrade *et al.*, 1996; Calviño *et al.*, 2003) and, therefore, it is an undesired effect from farmers perspective.

1.5. The development of irrigated permanent beds systems

In certain situations farmers decide to grow crops using beds-furrows systems. That is, plants are located in soil zones raised by ridging (bed) that alternate with a depression (furrow). Beds may be prepared every year as in conventional agriculture, or maintained in space and time as in conservation agriculture. In the permanent bed planting system (PB), soil disturbance is limited to reshaping the furrows when necessary. PB consists of planting the crops on the top of the beds, confining the traffic to the furrows, and maintaining residues from the previous crop. Beds can vary in width (0.25-2.00 m) and in the number of crop rows on each bed. For example, Devkota *et al.* (2013) sowed two rows of maize plants on 0.6 m wide beds at the top (0.9 m between furrows), while Driscoll (2013) sowed one row of maize plants in 0.36 m wide beds at the top (0.73 m between furrows).

The decision to grow crops on beds, permanent or not, may be motivated by (i) the irrigation method, i.e. furrows between beds are required to apply irrigation water; (ii) the need for avoiding waterlogging risks in the part of soil where seedlings grow and most roots concentrate (Song *et al.*, 2013); and, (iii) the interest on advancing sowing date thanks to the bed shape which results in increased solar radiation interception, limited heat transfer between beds and deeper soil and improved drainage (Mahrer and Avissar, 1985; Benjamin *et al.*, 1990). In raised bed systems, the displacement of machinery across the field is improved, reducing the need for intervention and the fatigue of the operator (Fausey, 1990). In the case of no-tilled soil, PB facilitates crop residues management by accumulating most of them in the furrows after clearing the top of beds where crops will be sown (Calleja *et al.*, 2008). As for other CA systems, PB may be adopted for reducing risks of soil erosion, irrigation applied and costs (Calleja *et al.*, 2008; Ram *et al.*, 2012) or for facilitating cropping intensification (Beecher *et al.*, 2006).

PB systems are studied in many regions around the word: Australia (Tisdall and Hodgson, 1990; Hulugalle and Daniells, 2005; Beecher *et al.*, 2006), India (Ram *et al.*, 2012), Mexico (Govaerts *et al.*, 2005, 2006), Spain (Boulal *et al.*, 2012), the USA (Driscoll, 2013) and Uzbekistan (Ibragimov *et al.*, 2011; Devkota *et al.*, 2013). In PB systems, water irrigation can be supplied by sprinklers (Boulal and Gómez-Macpherson, 2010; Boulal *et al.*, 2012) or by furrow irrigation (Govaerts *et al.*, 2005; Driscoll, 2013; Devkota *et al.*, 2013). In the last cases, if crop residues make more difficult the advancement of water along the furrows, it will then be preferred the application of irrigation water in alternate furrows while crop residues are raked into not irrigated furrows (Driscoll, 2013).

In general, PB with crop residues has no clear effect on crop yield with positive (Hulugalle and Daniells, 2005; Boulal *et al.*, 2012), negative (Ibragimov *et al.*, 2011) or neutral effects (Govaerts *et al.*, 2005; Boulal *et al.*, 2012; Ram *et al.*, 2012). PB has similar benefits and constraints than other CA systems regarding effects on soil properties. When compared with conventional bed plantings, PB has demonstrated capability for increasing soil organic matter, aggregates stability and soil water infiltration and for reducing soil erosion (Hulugalle and Daniells, 2005; Hulugalle *et al.*, 2010; Ibragimov *et al.*, 2011; Boulal *et al.* 2011a; Ram *et al.*, 2012; Driscoll, 2013). These benefits are clearly observed when crop residues are maintained. However, managing the large amount of biomass produced by these irrigated systems is a challenge for adopters (Hulugalle and Daniells, 2005). Crop residues also decreased soil temperature at emergence and may result in poorer crop establishment and lower yields (Ibragimov *et al.*, 2011; Ram *et al.*, 2012).

PB may also result in higher soil compaction (Verhulst *et al.*, 2010; Boulal *et al.*, 2012; Ram *et al.*, 2012) with similar conflicts as in other CA systems (see Section 1.3). In the case of Boulal and Gómez-Macpherson (2010) and Boulal *et al.* (2012), PB was combined with CT to confine soil compaction and reduce its negative effects on the crop. As mentioned above, the system also facilitates crop residues management, another major problem in irrigated CA systems. The initial results of studies in which PB was compared to conventional bed planting, both combined with CT, have shown that in the short term there is no penalty for yield under PB and that there is spatial variation not only of soil compaction but also of SOM, soil water infiltration and runoff (Boulal *et al.* 2011a; Boulal *et al.*, 2011b). Further spatial variation may be created in hill-slope landscapes by runoff water transporting crop residues and sediments toward lower areas in the foot-slope during typical heavy rainfall events in the Mediterranean climate (Boulal and Gómez-Macpherson, 2010).

The scale of study is important in erosion studies as measured erosion rates depend on slope steepness, slope length and soil texture (Cerdan *et al.*, 2010). The limits imposed in experimental plot are contrived (De Ploey, 1989; Wainwright *et al.*, 2008). Thus, the result of erosion and sediment deposition at catchment scale is not the result of adding what happens at the scale of small plots (Govers and Poesen, 1988; de Vente and Poesen, 2005; Parsons *et al.*, 2006). At the catchment scale, factors like size, topography, morphology, and farm management are integrated (Casalí *et al.*, 2008). In general, plot measurements may result in an underestimation of the effectiveness of CA to mitigate erosion at catchment scale (Leys *et al.*, 2010). Furthermore, in irrigated systems the catchment scale is becoming the preferred domain for irrigation performance assessments (Barros *et al.*, 2011).

1.6. Objectives of this Ph.D. Thesis

Initial studies on irrigated maize-based permanent beds planting system (PB) combined with controlled traffic have shown positive short-term effects on water infiltration, erosion control and carbon sequestration with no penalty in crop growth and yield (Boulal et al., 2011a, 2011b, 2012). The aim of this Ph.D. Thesis is a longer term evaluation of this system in terms of soil and water conservation as well as crop growth and production, considering spatial and scale variations and paying attention to the evolution of possible constraints.

The particular objectives of the thesis are:

(a) to evaluate longer term effects of PB combined with controlled traffic on crop growth, yield and water use efficiency;

(b) to evaluate a precision subsoiling operation for reducing soil compaction and improving root growth and yield in PB;

(c) to characterize the evolution of crop residues on the ground, soil quality, and soil CO_2 effluxes considering temporal and spatial variation due to tillage and traffic regimes;

(d) to estimate carbon sequestration potential of PB under our local conditions;

(e) to assess PB performance for erosion control at the catchment scale.

The Thesis is presented as chapters of which three have the structure of scientific articles (Chapter 3 have been accepted already). Specific objectives a, b, d and part of c are addressed in Chapter 2; the characterization of soil CO_2 effluxes (specific objective c) is addressed in Chapter 3; and specific objective e is addressed in Chapter 4. A general discussion of these three chapters is presented in Chapter 5 and the overall conclusions are shown in Chapter 6.

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Chapter 2 - Permanent bed planting with controlled traffic in a maize-based irrigated system in Mediterranean conditions: Effects on soil quality, below and above-ground crop growth and yield

ABSTRACT

Permanent bed planting (PB) combined with controlled traffic appears to be a promising system for improving sustainability of irrigated maize-based systems in Mediterranean conditions. This Chapter reports mid-term findings in a field experiment where PB is compared to a conventional system in which the beds are formed annually (CB). Additionally, a precision decompaction treatment was imposed on part of PB as a third planting system (DPB). Traffic was controlled during the study in a manner that furrows with traffic (F+T) alternated with furrows without traffic (F-T). Comparisons were made throughout a crop sequence of maize (*Zea mays* L.)–cotton (*Gossypium hirsutum* L.)–maize. Six years of experiment resulted in higher soil compaction and lower root density (0.6 m top soil layer) in PB than CB. However it had limited effect on crop above ground growth, yield and water use efficiency. In DPB, decompaction of trafficked furrows rather than increasing root growth reduced it due to a paraplow-pan created deep in the soil (0.4 m). In both PB and DPB, root density under F-T and the bed, and in deep soil layers (0.6-1.0 m), appear to provide required nutrients for maintaining above-ground growth. Controlled traffic resulted in spatial variation of soil compaction, plants residues and soil organic concentration (SOC) concentration in the permanent planting systems. In these systems, crop residues tended to accumulate on furrows and this, in turn, increased SOC in the top 0.05 m superficial layer that stabilized at higher values than on beds (1.67 vs. 1.09%, respectively). In DPB, SOC in F+T superficial soil (1.52% in the 0.05 m top layer) was reduced due to subsoiling. The absence of soil tillage in PB resulted in higher superficial SOC compared to CB but no significant differences were observed in deeper layers. On the contrary, SOC storage was 5.7 Mg ha^{-1} significantly higher in PB compared with CB for 0.5 m top soil layer. The difference for the full 1-m studied profile (8.7 Mg ha^{-1} more carbon in PB than CB) was not significant.

2.1. Introduction

Conservation agriculture (CA) is seen as a way of producing food and fibre while improving soil quality and minimizing environmental risks associated with farming practices (Hobbs *et al.*, 2008). In annual-crops based systems, adopting CA is expected (i) to increase soil organic matter (SOM) and improve associated soil properties by reducing or eliminating tillage, (ii) to directly protect the soil by maintaining crop residues covering the ground and reduce erosion and concomitant pollution, and (c) to enhance biota in the soil and the entire agrosystem (FAO, 2012). However, some of the positive effects of adopting CA will appear in the medium or long term, e.g. a significant SOM accumulation may be observed only after several years or cropping seasons (Verhulst, Kienle, *et al.*, 2010).

In CA annual-crops based systems, crop residues on the soil surface may accumulate over time beyond a manageable amount, particularly under irrigation when highly productive crops are cultivated (Gómez-Macpherson *et al.*, 2009), and this difficulty is one of the causes for the low rates of CA adoption. The amount of crop residues maintained on the ground decrease with time depending on the crop, on how and when stacks are slashed, and on prevailing environmental conditions (Ordóñez-Fernández *et al.,* 2007; Baker and Saxton, 2007). Another negative aspect of adopting CA in annual-crops based systems may be soil compaction associated to the lack of tillage (Blevins and Frye, 1993), particularly in irrigated systems and clay soils because of the potentially high soil water content (SWC) (Murray and Grant, 2007). Soil compaction may affect soil biotic and abiotic processes like nitrogen cycle and gases exchange between soil and atmosphere (Hamza and Anderson, 2005). In the conventional agricultural systems tillage offers the advantage of reducing soil compaction although the effect may be temporary (Lal and Shukla, 2004).

In southern Spain, a recently developed planting system in which annual crops are grown on irrigated permanent beds (PB) combined with controlled traffic (Boulal and Gómez-Macpherson, 2010) has demonstrated in the short term its capability to manage high amount of crop residues, to improve soil quality and to reduce soil erosion risk without yield penalty relative to conventionally tilled beds also combined with controlled traffic (Boulal *et al.*, 2011a; Boulal *et al.*, 2012). These benefits were observed soon after the establishment of an experiment in which PB was compared with conventional beds. The study lasted three years, however, some negative impact may be hidden behind the lack of observable crop penalization or may appear after years of CA adoption (Govaerts *et al.*, 2005). Understanding long term evolution of both soil compaction - crop growth interactions and maintenance of crop residues - SOC dynamic interactions are necessary to determine PB viability over time. Chapter 2 presents mid-term results corresponding to year four to six of the experiment established by Boulal *et al.* (2012). The objective was to deepening on PB longer term effects on crop growth, yield and water use efficiency (WUE), as well as on soil quality and heterogeneity, considering the spatial variation developed by tillage and traffic regimes. Additionally, a precision decompaction treatment was imposed on part of PB system to assess this strategy as a potential remedy for soil compaction without losing CA benefits. Although PB planting systems have been developed and tested around the world (Govaerts *et al.*, 2006; He *et al.*, 2008; Verhulst, Kienle, *et al.*, 2010; Ibragimov *et al.*, 2011; Ram *et al.*, 2012; Devkota *et al.*, 2013), we have not identified studies in Mediterranean conditions and we are not aware of any example in which PB was associated to controlled traffic.

2.2. Materials and methods

2.2.1 Experimental site, planting systems and farming operations

The research site is located at the *Alameda del Obispo* experimental farm (latitude 37° 51’ N, longitude 4° 47’ W, altitude 110 m) in Córdoba, Spain. The climate in the area is Mediterranean with mean annual rainfall of 536 mm, most of which concentrates among late autumn and early spring. Figure 1 shows the average minimum and maximum air temperature, monthly rainfall and irrigation depth applied during the study. The soil is *Typic Xerofluvent* (Soil Survey Staff, 2010) or *Eutric Fluvisol* according to FAO system (IUSS, 2006), with loam texture and without apparent restriction for root growth to 2-m depth. Particle-size distribution in the upper (0-0.15 m) soil layer consisted of 350 g kg $^{-1}$ sand, 443 g kg^{-1} silt and 206 g kg^{-1} clay.

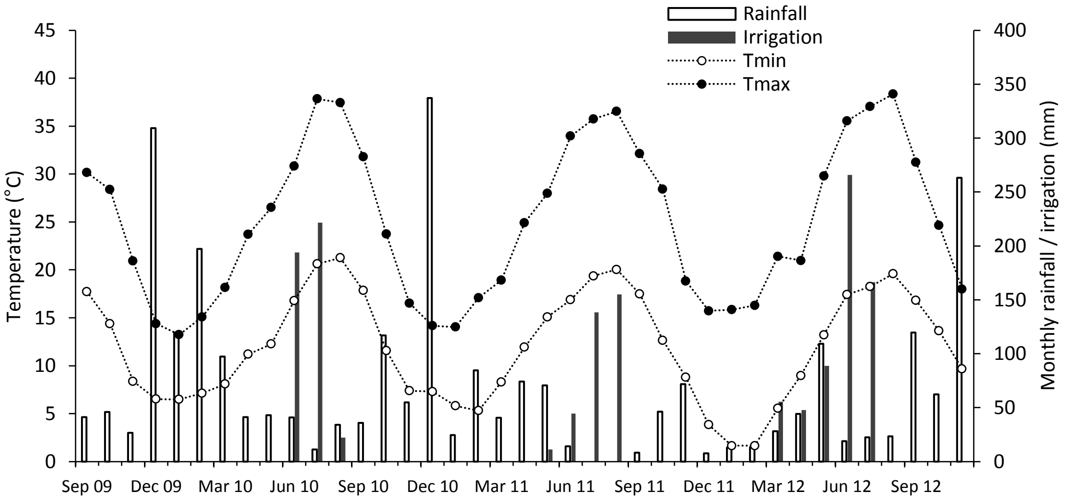

Figure 1. Monthly cumulative precipitation (rainfall and irrigation) and average maximum and minimum temperature from September 2009 to September 2012 at the experimental site.

This study was conducted during three years (2010–2013) in a long-term trial set up in 2007 to compare permanent- and conventional-bed planting systems, combined with controlled traffic, in a maize (*Zea mays* L.)–cotton (*Gossypium hirsutum* L.) rotation with sprinkler irrigation (Boulal *et al.*, 2012). In 2010, a new treatment was added so that three different bed planting systems have been compared since then: (*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 subsoiling was practiced before sowing on those furrows that supported traffic (decompacted permanent-bed planting system, DPB). Beds in both PB and DPB were not reshaped since they were formed in 2007.

The experimental plot covered 0.8 ha divided into three blocks. From 2007 to 2009, the blocks were subdivided into two plots, each of them consisting of ten 0.85-m-spaced furrow–bed sets with either CB or PB established. In March 2010, the three plots devoted to PB treatment were subdivided and DPB was established in one side, occupying four furrow–bed sets. The remaining six furrow–bed sets continued as PB. The separation between two contiguous trafficked furrows (1.7 m) was imposed by the width of the tractor used (model *ME9000 DTL*, Kubota Corporation, Thame, UK). Traffic was controlled in the whole experiment, and furrows with tractor wheel traffic (F+T) alternated with furrows without traffic (F-T). In CB, traffic was random during tillage for soil preparation but controlled after beds were formed. The number of wheel passes supported by F+T furrows during a cropping season varied across the experimental plot; sowing and slashing operations affected every single F+T furrow, but only some of these furrows were transited during the application of fertilisers and pesticides. Additionally, in DPB, F+T supported one extra wheel pass during the subsoiling operation. In this study, furrows with five wheel passes in PB and CB and six passes in DPB were selected as F+T furrows.

Details about planting systems, farming practices and traffic of machinery from 2007 to 2009 may be consulted in Boulal *et al.* (2012). Details of the main farming operations carried out from late 2009 to late 2012 are shown in Table 3. Maize was cultivated in 2010 and 2012 seasons and cotton in 2011 season. Maize sowing density was increased in 2010 to reduce bird damage at emergence whereas nets were used in 2012 using conventional seed density. Weed control was carried out using herbicides and, in the case of CB in 2011, by passing a cultivator. All the operations but harvests (manual) were performed by means of tractor. The main tractor used in this study was the *Kubota ME9000*, of 2.9 Mg of weight and tires of 0.38 m width, 1.32 m apart. A second tractor (*Kubota M120 DT*, 4.1 Mg of weight) was used during CB subsoiling, disking, and vibrocultivator pass. In DPB, the zone subsoiling was carried out by passing a single leg of a paraplow on every trafficked furrow up to 0.35 m depth.

Table 3. Farming operations performed at the experimental plot during the study.

Date	Operation	System
9-Nov-09	Herbicide application: Glyphosate 36%, 13 L ha^{-1}	All
6-Apr-10	Slashing of standing cotton stems	All
	Herbicide application: Glyphosate 36%, 6 L ha^{-1} + Oxifluorfen 48%, 2 L ha^{-1}	All
7-Apr-10	Subsoiling to 0.55 m, three chisels 0.675 m apart	CB
8-Apr-10	Subsoiling of trafficked furrows to 0.3 m; two chisels 1.7 m apart	DPB
	Disc pass (harrow disc *Tagra* , La Rambla, Spain) (0.2 m)	CB
	Vibrocultivator pass (*Noli* mod. V-C-C, Fernán Núñez, Spain) (0.25 m)	CB
	Bed formation: 0.85-m spaced bed/furrow sets	CB
10-Apr-10	**Maize** (cv. *Sancia*) **sowing**, 120,000 seeds ha^{-1}. Insecticide applied with seed: Chlorpyrifos 5%, 4.6 kg ha^{-1}	All
12-Apr-10	Fertilization: complex fertilizer 15-15-15-15% (N-P-K-S), 750 kg ha^{-1}	All
7-May-10	Herbicide application: 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	Insecticide application: Chlorpyrifos-Methyl 22.4%, 2 L ha^{-1} + Abamectin 1.8%, 1 L ha^{-1}	All
10-Sep-10	Harvest	All
9-Feb-11	Slashing of standing maize stalks	All
7-Apr-11	Herbicide application: Glyphosate 36%, 7.5 L ha^{-1}	All
13-Apr-11	Subsoiling of trafficked furrows to 0.35 m; two chisels 1.7 m apart	DPB
27-Apr-11	Subsoiling to 0.55 m, three chisels 0.675 cm apart	CB
	Disc pass (harrow disc *Tagra* , La Rambla, Spain) (0.2 m)	CB
	Vibrocultivator pass (*Noli* mod. V-C-C, Fernán Núñez, Spain) (0.25 m)	CB
	Bed formation: 0.85-m spaced bed/furrow sets	CB
11-May-11	**Cotton** (cv. *Coko*) **sowing**, 300,000 seeds ha^{-1}. Insecticide applied with seed: Chlorpyrifos 5%, 5 kg ha^{-1}	All
13-May-11	Herbicide application: Fluometuron 50%, 3.1 L ha^{-1} + Glyphosate 36%, 3.8 L ha^{-1}	All
23-Jun-11	Inter row flexible arms cultivator pass (weeding), 0.05-0.1 m deep	CB
28-Jun-11	Fertilization: Urea, 150 kg ha^{-1}	All
7-Jul-11	Insecticide application: Thiacloprid 48%, 0.2 L ha^{-1}	All
12-Jul-11	Fertilization: Urea, 150 kg ha^{-1}	All
29-Sep-11	Harvest	All
18-Oct-11	Slashing of standing cotton stalks	All
19-Jan-12	Herbicide application: Glyphosate 36%, 6 L ha^{-1} + Oxifluorfen 48%, 2 L ha^{-1}	All
23-Feb-12	Subsoiling to 0.55 m, three chisels 0.675 m apart	CB
24-Feb-12	Disc pass (harrow disc *Tagra* , La Rambla, Spain) (0.2 m)	CB
	Vibrocultivator pass (*Noli* mod. V-C-C, Fernán Núñez, Spain) (0.25 m)	CB
	Bed formation: 0.85-m spaced bed/furrow sets	CB
7-Mar-12	Subsoiling of trafficked furrows to 0.35 m; two chisels 1.7 m apart	DPB
13-Mar-12	Herbicide application: Terbuthylazine 21.4%, 2.5 L ha^{-1} + Acetochlor 45%, 2.5 L ha^{-1}	All
14-Mar-12	**Maize** (cv. *Sancia*) **sowing**, 90,000 seeds ha^{-1}. Insecticide applied with seed: Chlorpyrifos 5%, 8 kg ha^{-1}	All
27-Mar-12	Fertilization: complex fertilizer 15-15-15% (N-P-K), 750 kg ha^{-1}	All
12-Apr-12	Fertilization: Urea, 150 kg ha^{-1}	All
26-Apr-12	Herbicide application: Terbuthylazine 50%, 2.5 L ha^{-1} + Fluroxypir 20%, 0.6 L ha^{-1}	All
27-Apr-12	Insecticide application: Chlorpyrifos-Methyl 22.4%, 0.6 L ha^{-1} + Abamectin 1.8%, 1 L ha^{-1}	All
16-May-12	Fertilization: Urea, 175 kg ha^{-1}	All
22-Aug-12	Harvest	All
13-Sep-12	Slashing of standing maize stalks	All

2.2.2. Crop emergence, growth and yield

Crop establishment was evaluated every year after plant emergence by determining the total number emerged plants and the distance between them in 1.5 m of two adjacent rows, counted at ten sites per plot for maize and three sites per plot for cotton on 4 May 2010, 20 May 2011 and 10 April 2012.

Four manual sampling of crop plants per season 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. Leaf area was measured with a leaf area meter (model *LI-3100* LiCor Inc., Lincoln, Nebraska, USA) and dry mass of each group of plant organs (leaves, stems and reproductive organs) was obtained after drying samples in a forced-air oven at 75 °C to constant weight.

Maize grain yield was determined from hand-harvested cobs (10 September in 2010 and 22 August in 2012) from 2 m of five adjacent rows (8.5 m^2) in five sites per plot. In each sampling, one of the five rows (1.7 m^2) was harvested separately to determine AGDM as well as the number of ears per plant, number of kernels per ear, and 1000-kernel weight. Harvest index was estimated as the ratio of grain dry mass and total above-ground biomass. Yield of cotton seed (including the lint) was determined by hand picking (9.4 m^2) in four sites per plot (29 September 2011). In one of the four rows, 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 and early August in 2012. The study was carried out following the trench excavated method using a backhoe loader that opened a single trench perpendicular to crop rows in blocks 1 and 3. Root intersections with the vertical plane of observation (number per unit area) were counted in all 0.1 by 0.1 m cells of a wire grid (Smit *et al.*, 2000). The grid (1 m deep and 0.9 m wide) was placed in such manner so that its centre coincided with a crop row (position 0) and covered the two adjacent furrows towards their centre: positions 1 to 4 in F+T and positions -1 to -4 in F-T, corresponding positions 4 and -4 to the centre of furrows (Figure 2).

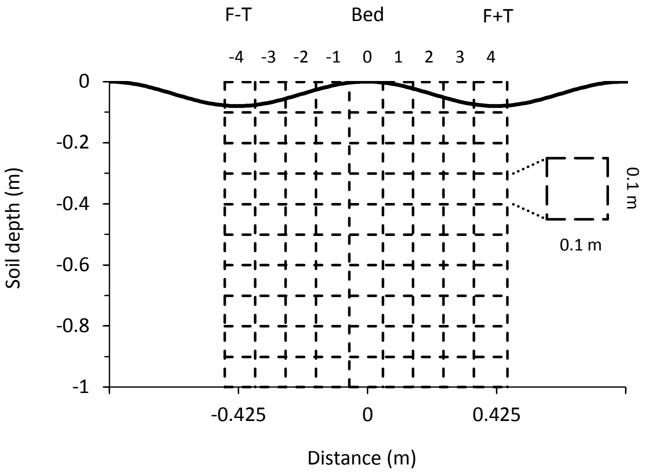

Figure 2. Sampling grid used for root assessing on trench walls in 2012 is located in relation with the bed and the furrows with and without wheel traffic (F+T and F-T, respectively) positions. Sites with and without traffic influence are also indicated with positive and negative numbers, respectively.

Roots counting was carried out in one bed/furrow site per planting treatment and block. Before that, the profile walls were scraped using a hand rake, removing 0.03 m of the soil approximately in the vertical plane to expose maize roots and facilitate their visualization. A soil core (0.05 in height, 0.05 in diameter) was taken horizontally using a soil corer in seven cells of contrasting root intersections in PB and CB transects (n=28). Roots contained in cores were washed gently using 0.063 mm-size sieve to remove mineral particles, dead roots and plant debris. Roots were stained with congo red to facilitate their identification 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 in the selected 28 cells was used to transform root frequency into values of root density.

2.2.3. Crop residues

The presence of plant residues on the soil surface was assessed in terms of covered area and plant residues biomass. The soil surface covered by crop residues was determined in furrows and beds using frames of 0.59 m x 0.50 m and 0.26 m x 0.50 m, respectively, photographing the framed areas, and processing the photos with the Environment for

Visualizing Images processing software *ENVI 4.7* (ITT Visual Information Solutions) to differentiate crop residues from the soil. After photographing, crop residues within the frames were collected. When necessary, samples were gently washed under a spray nozzle in order to obtain crop residues free of soil particles. All components were dried at 75 °C to constant weight and residue mass per unit of soil area was calculated. Samplings took place on 14 October in 2009 (only biomass), 23 March and 4 November (only ground cover) in 2010, 13 May and 22 October in 2011, and 30 March and 20 November in 2012.

2.2.4. Soil water content, evapotranspiration and irrigation scheduling

SWC was measured up to 1.95 m deep, starting at 0.15 m, and then every 0.3 m for the rest of the profile. Measurements were made using a neutron probe (*503DR Hydroprobe*, CPN International Inc., Martinez, USA) on five access tubes per plot in two blocks only, i.e. 30 tubes in the entire experiment. In general, readings began around sowing and were performed every week/two weeks during the irrigation period, and again around harvest. SWC data was used to calculate crop evapotranspiration (ET) as the sum of ET values between consecutive soil water storage readings by means of a soil water balance:

$$\Sigma ET = \Delta SWC + R + I \qquad (1)$$

where ΔSWC is the difference of SWC between two consecutive SWC readings, R is the rainfall and I is the irrigation accumulated during the same period. Runoff and deep percolation were assumed negligible. Water use efficiency (WUE) was calculated as the ratio of yield or total AGDM at harvest and ET.

The amount of water to be applied per irrigation was calculated weekly 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. Estimated water storage at field capacity was 0.24 m^3 m^{-3}, and at wilting point, 0.12 m^3 m^{-3}.

2.2.5. Soil compaction

Soil cone index (CI) was measured using a soil cone penetrometer with a 30° circular stainless steel cone with a base diameter of 12.83 mm coupled to a portable computer (model *HINKA-2010* v1.0, Agrosap S.L., Spain) and following ASABE standards (2009a and 2009b). CI determinations were made in beds and adjacent trafficked and untrafficked furrows in three sites per plot in May, August, and December 2011, and in November 2012. Extra CI determinations were done in bed shoulder positions, i.e., in between the centre of the bed and the centre of the furrow, during the sampling of November 2012. Each CI value was obtained by averaging five measurements. One value of CI was obtained every 0.01 m deep and down to 0.60 m deep, except in August 2011 (0.3 m) due to excessive soil strength. SWC for the top 0.6 m soil (0.3 m in May 2011) was measured concomitantly to CI determinations. CI data was analysed considering soil layers of 0.5 m.

Soil bulk density (ρ) was determined from soil cores of 0.05 in height and 0.05 m in diameter at 0.05-0.1, 0.2-0.25, 0.35-0.4, 0.5-0.55 and 0.65-0.7 m depth after drying at 105 °C for 48 h. Samplings were carried out in June 2011 and January 2012 in three sites per plot, in beds and in the two adjacent furrows (with and without traffic) of the three planting systems.

2.2.6. Soil organic carbon content

Soil samplings were carried out for determining soil organic carbon concentration (SOC) in 0.0-0.05, 0.05-0.1 and 0.1-0.3 m soil layers in beds and adjacent furrows (with and without traffic) of the three planting systems on 19 April 2011, 23 January 2012 and 22 November 2012. One extra soil sampling was performed in CB only in 6 June 2011 (40 days after the tillage sequence for bed forming). Two soil cores 1-m apart were taken in three sites of every plot. The three layers of the six cores (0.05 m in diameter) were used to form composite samples per layer and plot. Composite samples were air-dried and passed through a 0.002-m sieve. SOC 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 to 1-m depth in PB and CB treatments. SOC concentration for 0.1 m layers was determined. SOC concentration (mass of organic carbon per mass of soil) was converted into SOC storage (SOCs) per unit area considering soil 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).

2.2.7. Statistical analysis

Treatments were compared by means of analysis of variance. Data for plant density, yield and yield components, ET and WUE were analysed as a randomized block design in spite of DPB being nested in PB. Data for soil ρ, CI and SOC were analysed within bed or furrows positions and soil layers. SOC storage and crop residues on the ground corresponding to a planting system was calculated by weighing the values obtained in each bed and furrow with or without traffic position according to the area that they represented (bed 50% and furrows 25% each). Mean values were separated using the Tukey's HSD means comparison test with a significance level of 5%.

2.3. Results

2.3.1. Soil compaction

Differences in CI with soil depth and treatments were relatively consistent over time. On one hand, CI was higher in beds and F+T furrows positions in PB than in CB; on the other, subsoiled F+T soil in DPB had the lowest CI when compared with F+T in PB and CB. Data are presented for 2012 only (Figure 3) as this sampling was the last one and it has the most complete set of measurements because it includes an additional sampling point at the bed shoulder. In general, bed positions tended to be less compacted than shoulders or furrows, particularly in CB. The average CI for the 0.6 m profile in the bed positions was 0.8 MPa in CB and 1.1 MPa in PB and DPB. In the rest of positions, particularly in the shoulders, soil profile also tended to be more compacted in PB and DPB than CB. Nevertheless, measured values in any PB position, included F+T, were lower than 1.8 MPa (for a SWC of 29%) in spite of having the soil undisturbed since 2007 (five years).

Wheel traffic increased CI in the centre of F+T and adjacent shoulder (S+T) compared with F-T (Figure 3). In the case of DPB, however, low CI values in F+T showed that subsoiling was effective in decompacting the soil up to 0.35 m depth. However, this operation compacted the soil below such depth (Figure 3e), having no effect on loosening the shoulder soil (Figure 3d). In CB, wheel traffic during cropping season increased CI in F+T position but obtained values for the top 0.3 m layer was significantly lower than those measured in PB.

Soil ρ by planting system, bed/furrow position and soil layer is presented in Table 4. Values were variable and significant differences were hardly detected. However, data shows similar trends as those observed in CI. In general, ρ was higher in beds in PB relative to CB and in furrows with wheel traffic relative to F-T. In DPB, subsoiling resulted in lower ρ in F+T superficial layers confirming the effectiveness of this operation on soil loosening.

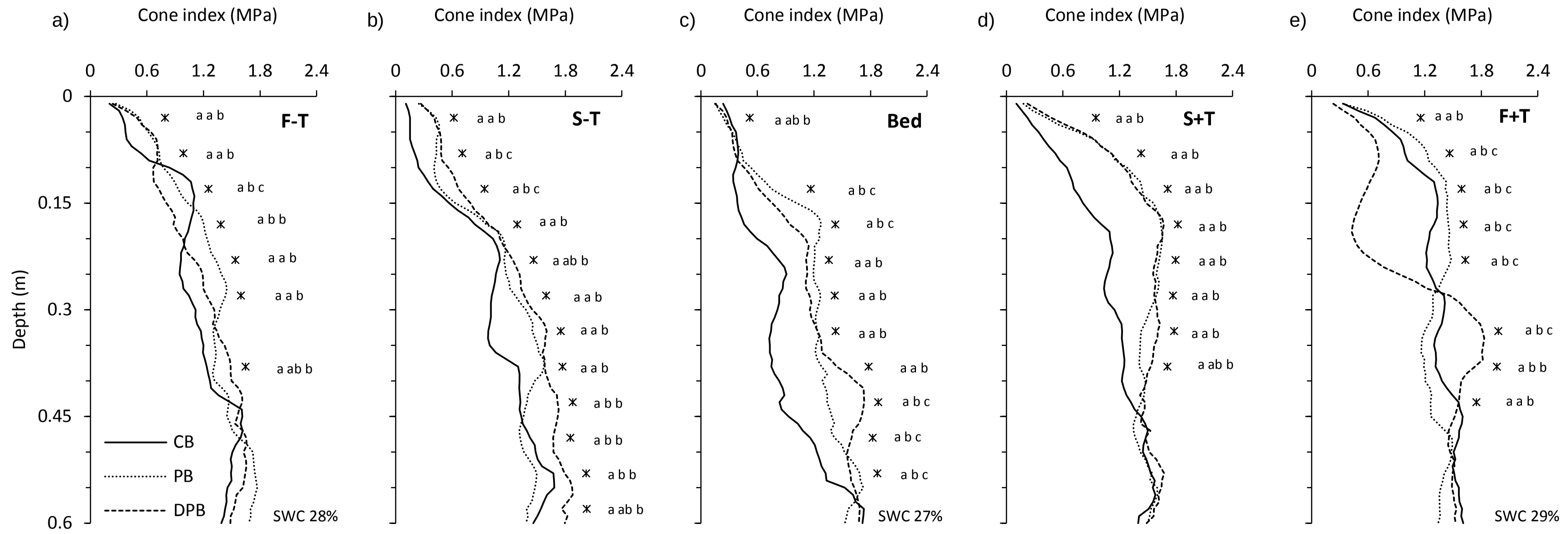

Figure 3. Soil cone index to 0.6 m depth in the permanent (PB), decompacted permanent (DPB) and conventional (CB) beds planting system and their corresponding soil positions (furrows with [F+T] and without [F-T] traffic, and beds) in November 2012. The average volumetric soil water content (SWC, %) for beds and furrows is shown in the body of each subfigure. The asterisk indicates significant differences of soil cone index among positions when 0.05 m soil layers were compared, in which case homogeneous groups are indicated with the same lower case letter (Tukey’s HSD means separation test at 5%).

Table 4. Soil bulk density (g cm^{-3}) at different soil layers in Beds, furrows with traffic (F+T) and furrows without traffic (F-T) in the permanent (PB), the decompacted permanent (DPB) and the conventional (CB) beds planting systems.

Planting system	Soil layer (m)	Soil bulk density (g cm^{-3})					
		June 2011			January 2012		
		F-T	Bed	F+T	F-T	Bed	F+T
PB	0.05-0.1	1.46 b	1.45 a	1.52 a	1.39 b	1.33 b	1.60 a
	0.2-0.25	1.56 ab	1.59 a	1.57 a	1.60 a	1.56 a	1.57 a
	0.35-0.4	1.57 a	1.60 a	1.53 a	1.51 ab	1.51 ab	1.52 a
	0.5-0.55	1.52 ab	1.60 a	1.58 a	1.55 ab	1.46 ab	1.52 a
	0.65-0.7	1.48 ab	1.51 a	1.48 a	1.48 ab	1.53 ab	1.51 a
DPB	0.05-0.1	1.42 b	1.38 b	1.47 a	1.45 a	1.40 b	1.43 a
	0.2-0.25	1.55 a	1.58 a	1.57 a	1.57 a	1.59 ab	1.62 a
	0.35-0.4	1.55 ab	1.59 a	1.57 a	1.60 a	1.67 a	1.60 a
	0.5-0.55	1.54 ab	1.56 a	1.47 a	1.50 a	1.55 ab	1.56 a
	0.65-0.7	1.49 ab	1.52 a	1.56 a	1.41 a	1.53 ab	1.50 a
CB	0.05-0.1	1.58 a	1.39 a	1.59 a	1.35 b	1.28 b	1.57 a
	0.2-0.25	1.59 a	1.48 a	1.56 a	1.61 a	1.44 a	1.60 a
	0.35-0.4	1.54 a	1.47 a	1.59 a	1.61 a	1.45 a	1.61 a
	0.5-0.55	1.55 a	1.48 a	1.49 a	1.52 a	1.57 a	1.48 a
	0.65-0.7	1.48 a	1.55 a	1.52 a	1.49 a	1.47 a	1.50 a

Values with the same letter within a column and planting system are not statistically different (Tukey's HSD means separation test at 5%).

2.3.2. Crop establishment, growth and yield

Crop establishment defined as plant density after emergence did not differ among planting systems (Table 5). However, in the maize crops, the standard deviation of measured distances between adjacent plants within a row was higher in PB and DPB than in CB indicating more irregular establishment in the formers. In maize, the number of plants per unit surface was higher in 2010 than in 2012 because of the higher sowing density as a mean of reducing bird damage at plant emergence (see *Material and methods* section).

Table 5. Plant density (mean ± standard deviation) and standard deviation of the distance between consecutive plants after emergence.

Crop	Year	Planting system	Plant density (pl m^{-2})	Standard deviation of distance between plants (m)
Maize	2010	PB	10.7 ± 1.5 a	0.058 ab
		DPB	10.4 ± 1.6 a	0.060 a
		CB	10.8 ± 1.4 a	0.051 b
	2012	PB	7.8 ± 1.2 a	0.057 a
		DPB	7.8 ± 1.2 a	0.059 a
		CB	7.5 ± 1.0 a	0.051 a
Cotton	2011	PB	14.1 ± 3.2 a	0.074 a
		DPB	13.6 ± 2.3 a	0.069 a
		CB	12.9 ± 2.8 a	0.080 a

Values within a year with the same letter are not statistically different (Tukey's HSD mean separation test at 5%).

In maize, AGDM tended to accumulate faster in CB than in PB or DPB at the beginning of the cropping season. These differences were maintained over time in 2010 but disappeared in 2012 (Figure 4). Additionally, in 2010, accumulated AGDM was generally higher in DPB than in PB, being significantly higher at harvest. Similarly, in this year grain yield was highest in CB, intermediate in DPB and lowest in PB, which also had the lowest HI (Table 6). In 2012, planting treatments did not differ in AGDM at harvest nor did in grain yield or HI. CB plots, however, yielded less than two years before because of lower ear density per unit surface that was not compensated by an increased grain biomass per ear (Table 6).

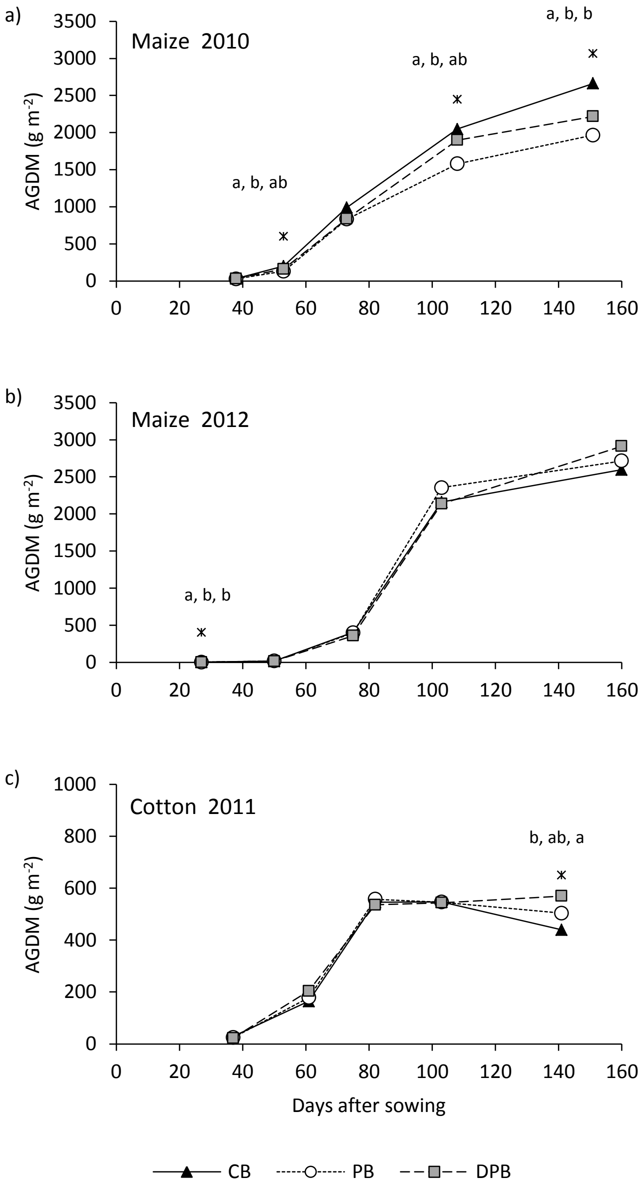

Figure 4. Above ground dry matter accumulated in maize and cotton plants throughout the growing season in 2010, 2011 and 2012.

Table 6. Yield components and harvest index (mean ± standard deviation) for maize and cotton at harvest moment, in each planting system and cropping season.

Crop	Year	Planting system	#Plants m^{-2}	#Ears per plant	Grain biomass per Ear (g)	1000 grains (g)	Grain yield ($g\ m^{-2}$)	Harvest index (%)	Plant height (m)	ET (mm)	WUE_{Yield} ($g\ l^{-1}$)	WUE_{AGDM} ($g\ l^{-1}$)
Maize	2010	PB	9.6 ± 1.0 ab	0.9 ± 0.1 a	132 ± 31.6 b	286 ± 21 b	1042 ± 250 c	53.1 ± 5.1 b	2.5 ± 0.2 b	847 ± 49 a	1.4 ± 0.1 b	2.5 ± 0.2 a
		DPB	8.9 ± 1.4 b	0.9 ± 0.0 a	156 ± 24.1 a	304 ± 25 a	1249 ± 152 b	56.4 ± 3.2 ab	2.6 ± 0.1 b	868 ± 22 a	1.5 ± 0.0 ab	2.7 ± 0.1 a
		CB	10.5 ± 0.9 a	0.9 ± 0.1 a	157 ± 21.4 a	290 ± 18 ab	1527 ± 115 a	57.4 ± 2.0 a	2.7 ± 0.1 a	858 ± 36 a	1.7 ± 0.0 a	3.1 ± 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	45.8 ± 5.6 a	2.8 ± 0.1 ab	868 ± 25 a	1.3 ± 0.1 b	3.1 ± 0.1 a
		DPB	8.3 ± 0.8 a	1.0 ± 0.0 a	200 ± 34.8 a	318 ± 39 a	1426 ± 232 a	48.9 ± 3.5 a	2.9 ± 0.1 a	835 ± 42 a	1.6 ± 0.2 a	3.3 ± 0.4 a
		CB	8.1 ± 0.5 a	1.0 ± 0.0 a	197 ± 36.0 a	310 ± 42 a	1272 ± 220 a	49.0 ± 2.6 a	2.7 ± 0.1 b	844 ± 26 a	1.4 ± 0.1 b	2.9 ± 0.2 a

Crop	Year	Planting system	#Plants m^{-2}	#Bolls per plant	Seed+Lint biomass per Boll (g)		Seed+Lint yield ($g\ m^{-2}$)	Harvest index (%)		ET (mm)	WUE_{Yield} ($g\ l^{-1}$)	WUE_{AGDM} ($g\ l^{-1}$)
Cotton	2011	PB	10.8 ± 2.9 a	4.3 ± 1.7 a	4.4 ± 0.8 a		185 ± 33 a	37.0 ± 3.0 a		585 ± 31 a	0.3 ± 0.0 a	0.9 ± 0.1 a
		DPB	11.2 ± 2.7 a	4.3 ± 1.1 a	4.4 ± 0.7 a		208 ± 55 a	37.0 ± 4.0 a		589 ± 35 a	0.4 ± 0.0 a	1.0 ± 0.0 a
		CB	11.2 ± 2.9 a	3.9 ± 1.8 a	4.5 ± 1.0 a		176 ± 45 a	40.0 ± 3.0 a		611 ± 21 a	0.3 ± 0.0 a	0.7 ± 0.0 a

Values with the same letter within a column and year are not statistically different (Tukey's HSD means separation test at 5%).

In cotton, AGDM did not differ among planting systems during the 2011 cropping season except at harvesting, when AGDM was significantly higher in DPB relative to CB (Table 6). The higher biomass did result in a slightly non-significant higher number of bolls per plant and seed and lint yield.

Below-ground crop growth was studied only in the 2012 maize crop, at the early grain-filling period (milk dough stage). Root density differed between planting systems (Figure 5). Globally, CB had 7% higher root density than PB for the whole studied profile (from approximately the centre of a furrow with traffic to the centre of the adjacent furrow without traffic, i.e. 0.9 m width by 1 m depth). Differences were even larger considering only the upper 0.6 m layer where most roots were present (Figure 5a). In the 0.6-1.0 m layer, however, PB had higher density than CB, particularly at positions in furrows without traffic influence (Figure 5b).

Root density was highest just under the plants' row (position 0) and decreased with distance towards the centre of furrows. In the top 0.6 m soil layer, root densities decreased with distance from position 0 more in trafficked than untrafficked furrows for equivalent positions, although not significantly (Figure 5a). The wheel traffic had higher effect on root density in PB than in CB and, interestingly, more in DPB than in PB. Although the subsoiling operation in DPB had reduced soil compaction in the centre of the furrow (position 4) (1.1 vs. 1.3 MPa in DPB and PB, respectively, on average for this soil layer), the compaction in the shoulder of the ridge was maintained (1.4 MPa in DPB and PB).

2.3.3. Evapotranspiration and water use efficiency

The SWC was higher in PB and in DPB relative to CB during part of the cotton and maize cropping season in 2011 and 2012, respectively. No differences were found during the maize 2010 season (Figure 6). When differences were observed, these decreased late in the season with the reduction of irrigation water applied followed to favour grain maturity. In the case of cotton, the irrigation cut was more severe in order to stop vegetative growth while favouring the opening of bolls.

Seasonal ET did not differ among planting systems in any cropping season (Table 5). Maize grain WUE was greater in CB relative to PB in 2010 and greater in DPB relative to CB and PB in 2012. No differences in WUE among planting systems were found when seed+lint yield (cotton, 2011) or total AGDB production (maize, cotton) were considered.

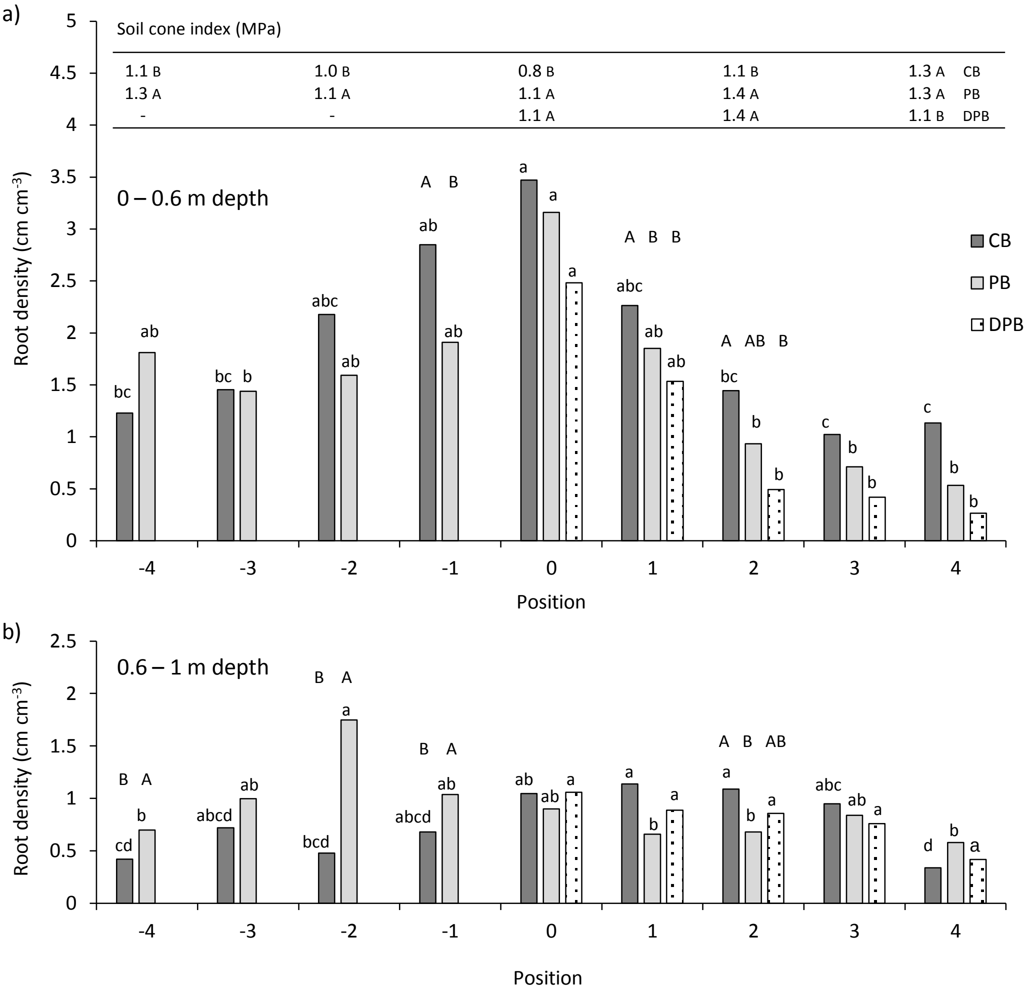

Figure 5. Root length density (cm cm^{-3}) in the 0-0.6 (subfigure *a*) and 0.6-1 m (subfigure *b*)-soil layers in the plant row (position 0), in trafficked (4) and untrafficked furrows (-4) and the in-between positions with and without influence of wheel traffic (1 to 3 and -1 to -3, respectively) in the conventional (CB), permanent (PB) and decompacted permanent beds planting systems. Average cone index value to 0.6 m depth (in MPa) obtained in November 2012 is shown within subfigure *a*. For each soil layer and planting system, positions with the same lower case letters do not differ in terms of root density. Planting systems in a same soil layer and position do not differ to each other when their root density bars are accompanied by the same upper case letter (upper cases letters are used only when significant differences exist). The Tukey's HSD means separation test at was applied at 5%.

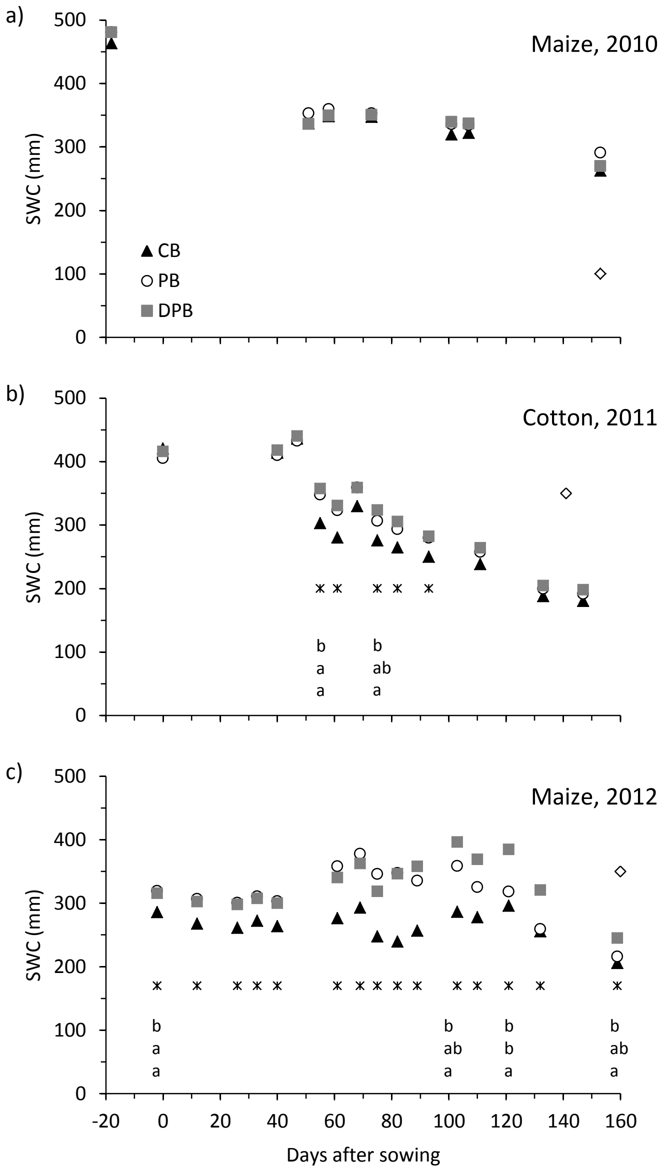

Figure 6. Soil water content (SWC) at the 0-2 m depth soil layer in the conventional (CB), permanent (PB), decompacted permanent (DPB) bed planting systems during maize (subfigures *a* and *c*) and cotton (subfigure *b*) cropping season. For each cropping season and measurement date the asterisk indicates that SWC differed significantly among planting systems. In those cases, letters indicate the SWC ranking. The Tukey's HSD means separation test at was applied at 5%. Same consecutive rankings are not shown to maintain the figure clear.

2.3.4. Crop residues and ground coverage

The evolution of crop residues biomass since the trial establishment in 2007 by bed/furrow position and planting system is presented in Figure 7. In PB, a greater amount of plant residues accumulated in furrows relative to beds positions, except when most crop residues were still standing, as in October 2009 and March 2010 (standing cotton stalks represented c.a. 85 % of crop residues) or immediately after slashing maize stalks in November 2012 when the stubble was homogeneously dispersed across positions. In CB, however, the amounts of maize stubble accumulated were higher in furrows than in beds in this last 2012 sampling. At that time, CB beds had been formed eight months before but they still maintained part of their shape with higher altitude than furrows; contrarily, the bed shape in PB had practically disappeared after six years and crop residues accumulated in furrows mostly because of the displacement during sowing operation. Regarding wheel traffic, no clear effect was observed on crop residues amount lying on the ground when F+T and F-T were compared. No effect was observed also of the subsoiling operation on F+T in DPB relative to the equivalent undisturbed F+T furrows in PB (Figure 7a).

In CB, crop residues were incorporated with tillage into the soil during soil preparation in spring. Thus, crop residues were on the ground between harvest and soil preparation, i.e. they protected the soil during autumn and most of winter. It is the time between soil preparation and full grown cover by crop that CB soil is less protected against water and wind erosion. By contrast, in PB system, the average amount of crop residues considering the spring samplings of the last three seasons only (2010 to 2012) was 6.2 Mg ha^{-1}. This is the approximate biomass that would protect PB soil in the early stages of crop growth.

Soil protection, however, is more dependent on ground surface covered by crop residues rather than biomass. We did not find a relationship between amount of plant residues and ground cover except in March 2010 sampling in CB system when ground cover was lower than 30% and soil preparation had not taken place yet (Figure 8). In autumn, ground cover was always above 50% in both, PB and CB, with crop residues biomass that varied from 3 to 12 Mg ha^{-1}. In spring, the percentage decreased to less than 50% although, in the case of PB system, values remained above 30% with crop residues biomass that varied from 2.8 to 9 Mg ha^{-1}. In DPB, subsoiling in F+T reduced the surface covered below 30% in some occasions (six out of 18 points) with biomass above 3 Mg ha^{-1} (Figure 8b).

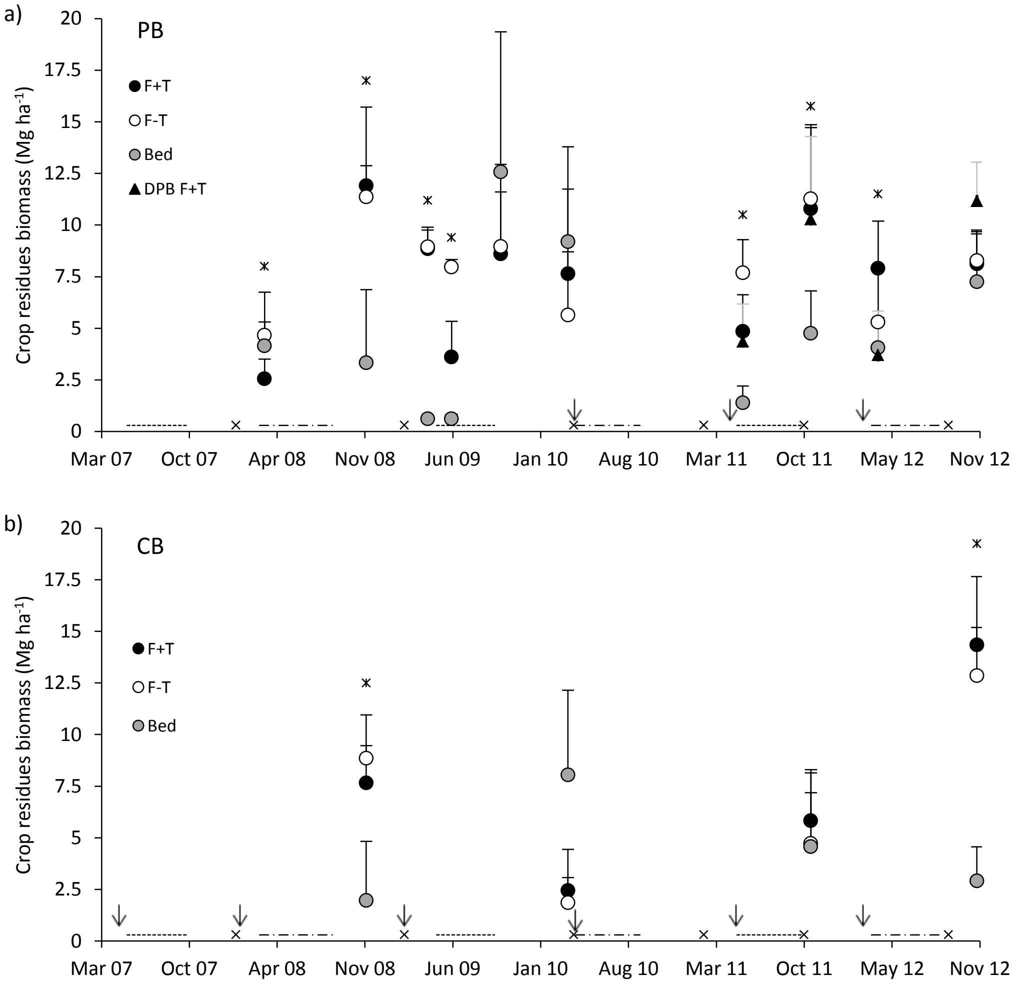

Figure 7. Biomass of crop residues laying on soil surface of Beds and furrows with (F+T) and without traffic (F-T) in different samplings from 2008 to 2012. Subfigures a and b correspond to the permanent (PB) and conventionally tilled (CB) beds planting systems, respectively. The bars indicate half standard deviation. The asterisks indicate significant differences among positions at each sampling date (Tukey's HSD means separation test at 5%). Subfigure a also contains data for F+T in DPB in the last four samplings (not included in the means comparisons). The corresponding bar is shown in grey. The arrows in Subfigure b indicate dates of soil tillage in CB; the dashed line indicates growing seasons for cotton as well as the dashed-dotted line does for maize; the crosses indicates dates of slashing of stalks.

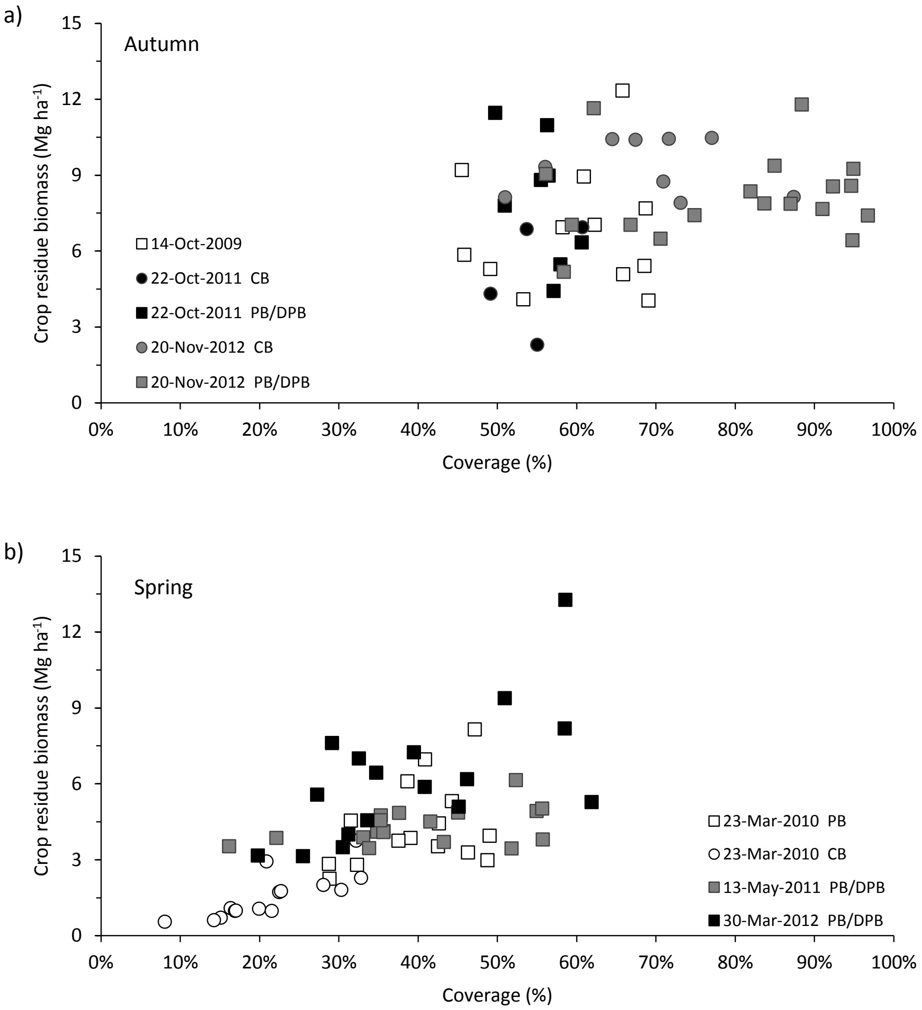

Figure 8. Relationship between soil area covered by crop residues (%) and crop residues biomass (Mg ha^{-1}).

2.3.5. Soil organic carbon

SOC in the top 0.05 m soil layer increased with time since the beginning of the experiment in 2007 but it did differently in the three planting systems and in the bed/furrows positions (Figure 9). SOC increased fastest in PB furrows with no difference between those with and without traffic (F+T is shown only for easier comparison with DPB): 0.326 and 0.120% y^{-1} for the first four years in furrows and beds, respectively. Furthermore, SOC in these furrows appears to stabilize at significantly higher concentrations than in the rest of positions. Considering the last three samplings, average SOC was 1.67% and 1.09% in PB furrows and beds, respectively. F+T in DPB tended to have lower SOC than F+T in PB, although with no significant differences in any sampling. The average SOC value for the last three samplings in decompacted F+T (DPB) was 1.52%. SOC also increased in CB during the first four years (0.096 % y^{-1}) at similar rate that in PB beds to reach a relatively stable value of 0.96% (average for bed and furrow positions in the last three samplings in CB). SOC was also determined down to 0.3 m in the same dates but few significant differences were observed (data not shown).

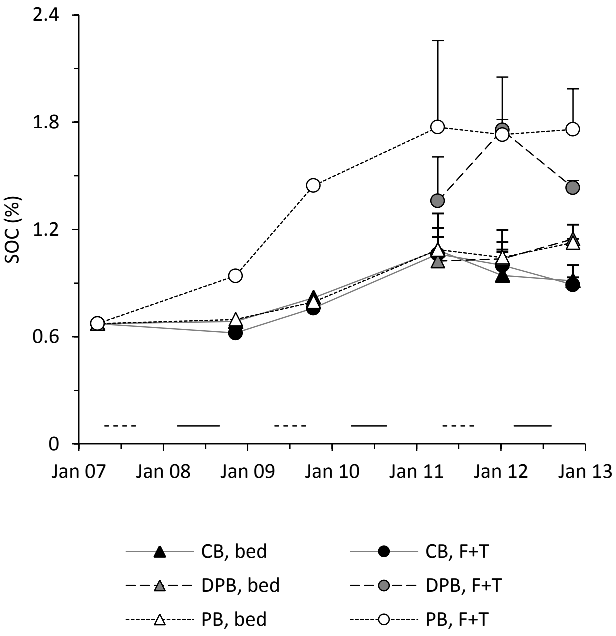

Figure 9. Soil organic carbon content (SOC, %) between 0 and 0.05 m depth in beds and furrows with traffic (F+T) in the permanent, decompacted permanent and conventionally tilled bed planting systems (PB, DPB and CB, respectively) from 2007 to 2012. Values from 2007 to 2009 were taken from Boulal et al. (2012). The bars used in the last three sampling dates indicate half standard deviations for sampling.

In spring 2011, the effect of soil preparation on SOC was determined in CB by carrying out an additional sampling 40 days after soil preparation. SOC had decreased 27% on average for all positions (bed, furrows) and layers (0-0.05 or 0.05-0.3 m) compared with SOC determined on 19 April 2011 (eight days before soil tillage and bed preparation).

In the last sampling at the end of the study (November 2012), soil samples were also taken from 0.3 to 1 m down in bed/furrow positions in PB and CB systems only (Figure 10). In all positions, SOC in the top 0.1 m layer was significantly higher in PB than in CB. These differences disappeared below this horizon although, in the furrows, there was a tendency to be higher in PB than CB. In the bed position, however, SOC in the 0.1-0.2 m layer was significantly higher in CB than in PB and the tendency continued down to the 0.4-0.5 m layer.

SOCs in PB and CB was also calculated down to 1 m (Figure 11) using soil ρ determined in January 2012 (Table 4) and SOC concentration determined in the last sampling (Figure 11). SOCs down to 0.5 m depth was significantly higher in PB than in CB (47 and 41 Mg ha^{-1}, respectively, for the top 0.5 m layer) but did not differ between planting systems below this depth. Considering the entire studied profile (1 m depth), global SOCs was 70 Mg ha^{-1} (averaged for the two systems).

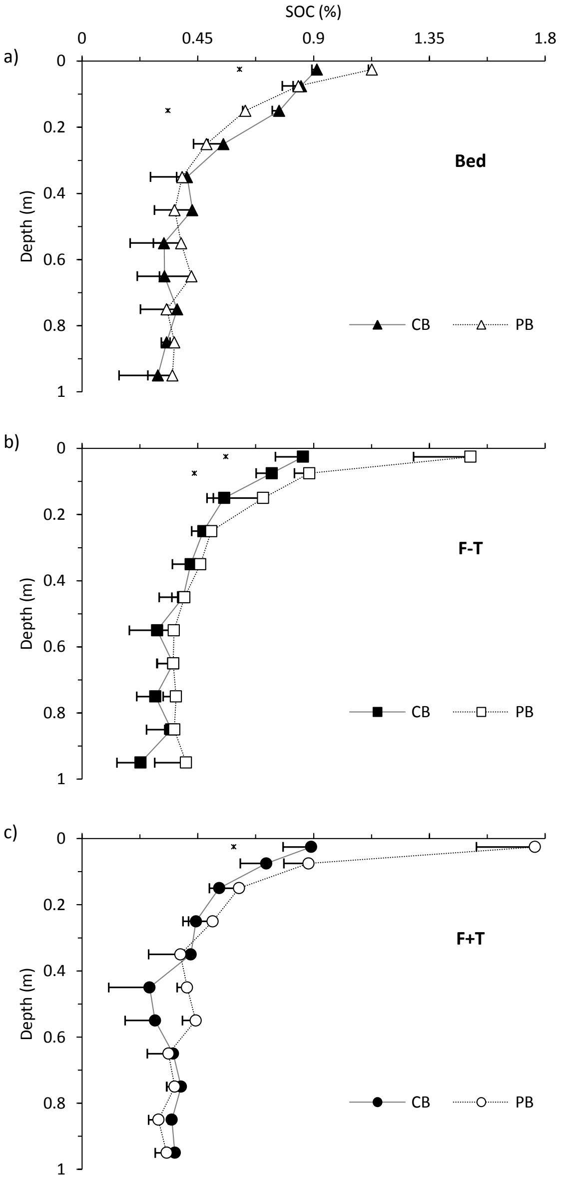

Figure 10. Soil organic carbon content (SOC, %) at the end of the study (November 2012) depending on depth and planting system. Subfigures *a*, *b* and *c* represent the beds, furrows with traffic (F+T) and without traffic (F-T), respectively. In each subfigure the asterisk indicates that differences between planting systems are statistically significant (Tukey's HSD means separation test at 5%).

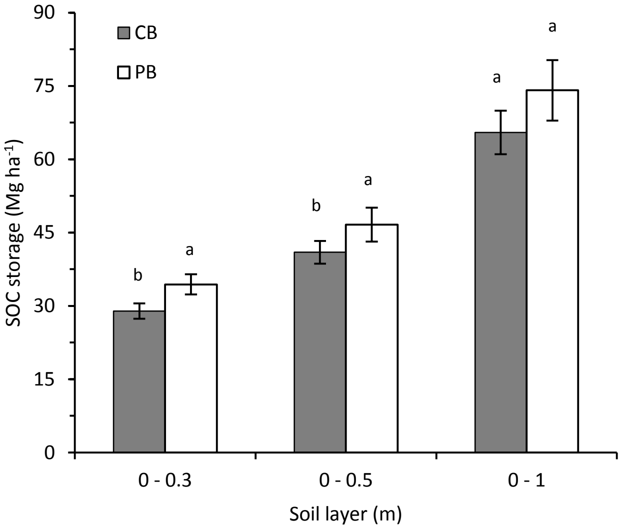

Figure 11. Soil organic carbon (SOC) storage in the 0-0.3, 0-0.5 and 0-1 m depth at the end of the study (November 2012). The bar indicates the standard deviation. Different letters in a same soil layer indicate that the value of SOC storage is statistically different between planting system (Tukey's HSD means separation test at 5%).

2.4. Discussion

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

In 2010, the first year of this study and fourth since the establishment of the experiment, differences in maize grain yield appeared among planting systems being the yield higher in CB than DPB and in DPB than PB (Table 6). These initial results together with the faster AGDM accumulation in CB and the confirmation of an increasing CI in the same order as grain yield (CB > DPB > PB), led to think that no tillage and the consequent lack of compaction alleviation in PB would have reduced crop growth and yield. However, no differences among planting systems were observed in cotton seed+lint yield in 2011 in spite of being cotton a crop with a root system of relatively high susceptibility to soil compaction (Materechera *et al.*, 1991), nor were there differences in maize yield in 2012 in spite of relative CI values consistent with earlier measurements (Figure 3). Reasons for 2010 results are not clear. Compared with CB, that year PB had at maturity one plant less per unit surface and lower grain yield, total plant biomass, biomass per ear and plant height, but similar kernel weight (Table 6). These differences indicate that the source of variation occurred before grain filling and in association to water or nutrient stress. SWC and calculated water balance suggest that PB plots did not suffer drought periods. On the other hand, unusually heavy rainfall accumulated from December 2009 to March 2010 (747 mm) before maize sowing would have resulted in considerable nitrates leaching (Moreno *et al.*, 1996; Bonaiti and Borin, 2010), particularly in PB (and DPB probably) because of its higher soil water infiltration (Boulal *et al.*, 2011). If the tillage conducted is also considered (Campbell, 1972), it is possible then that higher amounts of soil nitrates were available for the crop in CB plots than in PB or DPB, where crops would mostly depend on applied fertilizers for its growth. Basal fertilizer was broadcasted in the three planting systems and would not be readily available in deeper soil layers. However, more nitrogen was expected to be available in CB due to soil disturbance compared with no-tilled soil (Doran, 1980; Alvarez and Steinbach, 2009). We would expect that crops in both PB and DPB would be affected similarly by the nutrient deficit but, somehow, in PB the crop was more stressed and had smaller ears, lower kernel weight and grain yield (the last being below expectation for local conditions) (Boulal *et al.*, 2012). The higher SWC in DPB (Figure 6) could reflect that this treatment had received more irrigation water because of its position within blocks closer to sprinkler lines. Previous irrigation evaluations do not confirm this but more thorough evaluations along all plots are needed to reject this possibility.

In 2012, planting systems did not differ in maize grain yield (Table 6) and the obtained values were in agreement with local experiences for similar type of cultivar (Aguilar *et al.*, 2007). The lack of differences among planting systems is in agreement with other studies in southern Europe that also compared conventional and CA systems (Khaledian *et al.*, 2010; Salmerón *et al.*, 2011). However, obtaining similar grain yields contrasts with observed differences among planting systems in soil compaction and below-ground crop growth. Compared with CB, soil was more compacted in PB and this resulted in less root density, particularly under F+T (Figure 5). PB also tended to have fewer roots in the upper soil layers and more in deeper layers in agreement with other irrigated maize studies (Mosaddeghi *et al.*, 2009) but contrary to the most general finding of having more roots in no-tilled top soil as in rainfed maize or other crop cereals (Bauder *et al.*, 1985; Kaspar *et al.*, 1991; Lampurlanés *et al.*, 2001; Muñoz-Romero *et al.*, 2010). Compared with tilled soil, shallower rooting in rainfed no-tilled soil is probably favoured by increased soil moisture (Dwyer *et al.*, 1996) whereas under irrigation water should not limit growth. It is possible that root growth in PB has been facilitated by macropores created by previous crops, up to 40% of total roots has been measured as recolonizing roots in maize (Rasse and Smucker, 1998), to reach deeper layers than CB.

Furthermore, root development under the crop row and F-T in PB appeared adequate for maintaining nutrients uptake and for sustaining similar above-ground growth and grain yield as in CB. Other researches have shown an effect of soil compaction on rooting depth but little effect on maize yield (Moreno *et al.*, 2003) or cotton growth (Busscher and Bauer, 2003) when water and nutrients availability are adequate, particularly if fertirrigation is possible. In this regard, some researchers concluded that there might be thresholds values of root density above which the absorption of nutrients would be guaranteed, being those thresholds dependent on the mobility of nutrient but it still remains unclear how much root biomass is needed, which architecture must roots adopt and how much volume of soil must be explored to meet above-ground tissues demand and allow potential plant growth (Bingham, 2001).

Subsoiling in F+T furrows of DPB, rather than favouring root growth, it decreased it to lower levels than in F+T PB, although again, roots in the rest of the soil was able to maintain growth and produce similar grain yield as the two other treatments. Subsoiling was effective reducing CI in the centre of F+T 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 shoulder (F+S) compaction (Figure 3). Other zone-tillage type than the subsoiling carried out in this study, e.g. with paraplow legs angled 45^o to the side (López-Fando *et al.*, 2007; Boulal and Gómez-Macpherson, 2010), may be more effective in decompacting the shoulder soil. Further research is required to evaluate these options.

Differences in WUE were observed only in maize grown in 2010, when calculated with grain yield because of the differences among planting treatments in this term of the ratio (Table 6). All planting treatments were irrigated with the same amount of water and little differences in ET were obtained. The mulch in PB and DPB probably reduced soil evaporation and this water should be available for plant transpiration. However, improved WUE due to lower water used in PB may be observed only if different water treatments are also included in the trial (Tolk *et al.*, 1999; Verhulst *et al.*, 2011). Further research with different water depth treatments is needed for deepening on the advantages of PB for improving WUE and implications for water savings and irrigation scheduling.

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

Most crop residues tended to fell on the bottom of furrows, particularly after slashing or sowing, as it happened in PB system since its establishment (Figure 7; (Boulal *et al.*, 2012). With time, the bed shape faded in PB and crop residues displacement towards furrows mostly occurred at sowing. For example, the lowest amount of crop residues in PB since June 2009 was observed in beds two days after cotton sowing in 2011 (1.4 Mg ha^{-1}). All the same, a significant amount of crop residues (4-5 times more) were accumulated on furrows protecting their soil surface from rain and runoff. Spring was the time with lower amount of crop residues on ground as they have degraded during the relatively mild Mediterranean autumn and winter. Nevertheless, in PB the average amount of crop residues in the spring samplings of the last three seasons (2010 to 2012) was 6.2 Mg ha^{-1}, which generally assured values of ground cover above 30% in the early stages of crop growth. This percentage of ground cover is considered the minimum for protecting the soil from rainfall impact (Renard *et al.*, 1991; Hobbs *et al.*, 2008), although studies should confirm it for local conditions.

We did not find a clear relationship between crop residues biomass and ground covered by this biomass but, in most cases, crop residues above 3 Mg ha^{-1} would cover 30% of soil ground or more (Figure 8). In DPB, subsoiling had little effect reducing crop residues biomass and, although it could reduce ground cover in some occasions, soil protection was generally assured. By contrast, in CB all crop residues were incorporated into the soil during its preparation for sowing. Tillage also loosened the soil and, therefore, the risk of water erosion was highest at this time (Boulal *et al.*, 2011a). However, in this study, crop residues were kept during autumn and winter protecting CB soil with ground covers above 50%.

The spatial and temporal differences in crop residues accumulation on the ground resulted in differences in SOC concentration in the top 0.05 m soil layer (Figure 9 and 10). In PB, SOC accumulated faster in furrows than in beds and stabilized at 1.67% whereas it did at 1.09% in beds (Figure 9). The difference between the two is linked to the higher amount of crop residues on the furrows and the slightly more favourable microenvironmental conditions (higher soil moisture, lower soil temperature during the day and higher soil temperature at night) for microorganisms activity (Muñoz *et al.*, 2007; Panettieri *et al.*, 2013), although not always (Limon-Ortega *et al.*, 2006). Other authors have shown a close link between amount of crop residues and SOC concentration provided humidity and temperature are not limiting (Karlen *et al.*, 1994; Blanco-Canqui and Lal, 2007). The rate of SOC increased in the top 0.05 m layer in furrows for the first four years was more than double the rate found on irrigated monocrop no-till maize in a similar soil in the region (Muñoz *et al.*, 2007). These authors did not provide information on crop residues production and the duration of the trial was not enough to reach a stable SOC value being their maximum SOC for the top 0.05 m layer (1.3%), which is below our results for PB furrows but similar if we would consider the system (beds and furrows).

In DPB, subsoiling tended to reduced SOC in the centre of F+T compared with the same furrows in PB but it results varied. Other studies in Spain have also shown reductions in SOC associated to subsoiling (López-Fando *et al.*, 2007) or to occasional vertical tillage (López-Garrido *et al.*, 2011; Melero *et al.*, 2011) on previously no-tilled cropping soils in cereal-based systems. Similarly, other operations that disturb the top soil in no-tilled systems, e.g. bed-reshaping, are also expected to reduce SOC (Shi *et al.*, 2012). We did not reform the permanent beds during the study but this is a common practice in other PB systems for facilitating furrow irrigation and favouring drainage (Verhulst *et al.*, 2011).

In CB, tillage reduced SOC by mixing the soil within the profile, by incorporating the stubble favouring its decomposition and by enhancing mineralization of organic matter due to aggregates disruption (Govaerts *et al.*, 2009). Nevertheless, since the establishment of the experiment, SOC in the top 0.05 m increased to 0.96% on average considering the last three samplings (Figure 9). This increase was partly due to the high 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 Follett *et al.* (2005) and partly due to time of sampling, which mostly took place several months after soil preparation given the opportunity to build up SOC (Carter, 2002). For example, the sampling carried out in CB 40 days after soil preparation in 2011 showed a decrease in SOC of 27% compared with values obtained in this planting system eight days before the tillage operations, i.e., in a soil that had not been tilled for one year. In the region, Ordóñez-Fernández *et al.* (2007) and López-Bellido *et al.* (2010) also reported increases of SOC in tilled treatments in the medium and long-term.

CA systems usually increases SOC in the top soil surface compared with conventionally tilled systems (West and Post, 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 top 0.1 m layer only (Figure 10) in agreement with other local studies in rainfed cereal-based systems (Murillo *et al.*, 2004; Hernanz *et al.*, 2009; Madejón *et al.*, 2009). Some authors argued, however, that incorporating crop residues would result in increasing SOC in conventional systems and that sampling should go deeper to detect these differences (Baker *et al.*, 2007; Govaerts *et al.*, 2009; Luo *et al.*, 2010). In this study, however, significant higher SOC in CB were only found in the 0.1-0.2 m soil layer in the bed position with no differences below 0.2 m. A similar pattern was found by Blanco-Canqui *et al.* (2011) who found no difference in deeper layers down to 1 m, as in our case.

Differences in SOCs between PB and CB were, however, significant down to the 0.5 m top soil layer (Figure 11) when the small differences in SOC concentration and ρ were combined. The difference in SOCs between PB and CB increased as a thicker soil layer was 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. The tendency for a higher SOCs in PB with increasing depth continued down to the 1 m profile (8.7 Mg ha^{-1} more carbon) probably due to the higher root density in deeper layers of PB. The PB potential for carbon sequestration compared with CB found in this study is less than half the potential estimated by (Boulal and Gómez-Macpherson, 2010) for a similar PB system (maize-cotton rotation, central pivot irrigation, permanent beds and controlled traffic) in a commercial farm in the province of Córdoba (13 Mg ha^{-1} for top 0.3 m soil layer). However they compared PB with an adjacent conventional plot not exactly equivalent to CB as it did not include controlled traffic, soil was tilled just after harvesting crops, and it had different order in crop rotation).

In Spain, most studies on the potential of CA for C sequestration in cereal-based systems had been carried out in rainfed conditions and for shallower horizons than in the study presented here (Álvaro-Fuentes and Cantero-Martínez, 2010; González-Sánchez *et al.*, 2012). On average, no-tilled systems stored 3.6 Mg ha^{-1} more carbon than the conventional systems (1.1 Mg ha^{-1} when compared with reduced tillage). Global reviews have obtained similar average SOCs increase in no-tilled compared to conventional systems: 4.9 Mg ha^{-1} (Angers and Eriksen-Hamel, 2008) and 3.4 Mg ha^{-1} (Virto *et al.*, 2012), both reviews considering layers at least 0.3 m deep. These average values are lower than that obtained in this study for irrigated conditions after six years of adoption; however, some local examples have resulted in similar or even higher levels of carbon sequestration after 11 years since adoption in rainfed conditions: 8.3 Mg ha^{-1} (0.9 m layer) (López-Bellido *et al.*, 2010) and 10.4 Mg ha^{-1} (0.52 m layer) (Ordóñez-Fernández *et al.*, 2007), although in vertisols with clay content around 70%.

The potential to sequester carbon in irrigated PB found in this study contradicts model predictions of soil carbon losses in irrigated systems under no-tilled because of fast crop residues decomposition in summer with high moisture and temperature (Álvaro-Fuentes *et al.*, 2012). Moreover, the studied PB system might further increase SOCs by changing cotton by wheat crops in the rotation (a low biomass producing crop by a high producing crop) and by increasing cropping intensity with a double crop system (Luo *et al.*, 2010).

2.5. Conclusions

Six years of PB resulted in higher soil compaction than CB but, by maintaining controlled traffic, compaction was mostly confined to furrows with traffic. Root density was lower in

PB than in CB but not to the extent of reducing above-ground growth or yield. Irrigation and biopores opened by previous crop probably counteracted any rooting limitation in PB caused by soil strength. In DPB, decompaction of trafficked furrows did not favour root growth but limited it by increasing compaction below the paraplow leg. A greater understanding of root system architecture and dynamics of root growth is needed to improve crop productivity and the efficiency in using nutrient and water.

Should compaction reach limiting levels for the crop, alternatives strategies for remediating soil compaction are needed. Any new option that implies soil disturbance would have to be evaluated for its effects on SOC and crop residues decomposition rate so superficial soil protection is maintained.

Controlled traffic in both conventional and permanent bed planting resulted in spatial variation of soil compaction, plants residues and SOC concentration, particularly in PB. In this last treatment, crop residues tend to accumulate on furrows. This increase in carbon input resulted in faster SOC (0.05 m superficial layer) and more stable values than on beds. These spatial differences were not observed in CB as soil was mixed with tillage. Soil disturbance resulted in lower superficial SOC in CB than PB but no significant differences were observed in deeper layers. On the contrary, SOC storage was 5.7 Mg ha^{-1} significantly higher in PB compared with CB for 0.5 m top soil layer. The difference was 8.7 Mg ha^{-1} for the full 1-m profile. The values are equivalent to C sequestered after 11 years relatively close rainfed studies in vertisols of high clay content. In principle, irrigation will enable further cropping intensification that in turns could further increase carbon sequestration. The implications at regional scale should be studied.

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Chapter 3 - Short and mid-term tillage-induced soil CO_2 efflux on irrigated permanent and conventional bed planting systems with controlled traffic in southern Spain

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ABSTRACT

Permanent beds combined with controlled traffic (PB) has been proposed as an alternative planting system for reducing soil erosion and compaction while increasing soil organic carbon (SOC) in irrigated annual-crop based systems in Mediterranean conditions. The objective of this study is to characterize, in space (beds and furrows with and without traffic) and time (hours, days and weeks), soil CO_2 efflux in PB compared with conventionally tilled bed planting (CB) and with a variant of the former (DPB) where subsoiling was performed in trafficked furrows. The three treatments were combined with controlled traffic. Tillage resulted in abrupt CO_2 effluxes that lowered rapidly within hours. However, in CB, soil CO_2 effluxes increased again significantly 12 days after tillage compared with PB or DPB. These differences were due to higher emissions from beds rather than from furrows where the soil had been compacted during the harrowing that formed the beds. In DPB, CO_2 effluxes increased in furrows with traffic after subsoiling and the effect was maintained during the study in spite of subsequent traffic. Soil CO_2 efflux increased with soil temperature (measured concomitantly) except after soil tillage. Tillage reduced SOC in both CB and DPB compared with PB.

3.1. Introduction

In southern Spain, soil loss by water erosion is a major environmental problem in annual-based cropping systems as farming management based on traditional tillage practices commonly leaves the soil uncovered. This is particularly relevant in irrigated systems established on sloping lands because crops are sown in spring towards the end of the rainy season (Boulal *et al.*, 2011). Conservation agriculture (CA) represents an alternative to this scenario. Its principles include minimum soil disturbance and soil coverage with crop residues, therefore protecting the soil by reducing raindrop impact and by increasing soil organic carbon (SOC) (Baker and Saxton, 2007; Verhulst *et al.*, 2010).

Irrigated permanent raised-bed planting systems have been developed around the world following the principles of CA (Govaerts *et al.*, 2005; Boulal and Gómez-Macpherson, 2010; Ibragimov *et al.*, 2011; Rochester, 2011), notwithstanding which, that or any other form of CA is rarely adopted by farmers in Mediterranean countries (Gómez-Macpherson *et al.*, 2009). A major limitation for its adoption is soil compaction resulting from the transit of machinery (Soane *et al.*, 2012). Controlled traffic and/or strategic zone-tillage have been proposed to reduce the negative effect of soil compaction on plant growth and yield (Taylor, 1983; Pierce *et al.*, 1992; Kingwell and Fuchsbichler, 2011; López-Fando and Pardo, 2012) but these options have not been combined with each other so far.

Another difficulty related with the practice of CA and that reduces its adoption in irrigated systems is managing the high amount of crop residues produced. Under raised-bed cultivation, however, crop residues tend to occupy the furrows leaving the top of beds rather clean (Boulal *et al.*, 2012). This uneven distribution results in higher SOC content in the top soil of furrows whereas, on the beds, the roots of crop plants promote the increase of SOC in deeper layers (Liebig *et al.*, 1993; Boulal and Gómez-Macpherson, 2010; Boulal *et al.*, 2012).

The soil organic material is degraded by microbial activity and this process releases CO_2 into the soil pore space. An immediate effect of tillage on soil CO_2 efflux regime is to promote an abrupt ejection of that CO_2 previously confined into the soil (Reicosky *et al.*, 1997; Álvaro-Fuentes *et al.*, 2007). Tillage also increases the production of ‘new’ soil CO_2 by favouring the oxidation of SOC that was previously protected between or within soil aggregates (Balesdent *et al.*, 2000) and of incorporated crop residues (Chantigny *et al.*, 2001). Although tilled soils usually emit greater amounts of CO_2 in comparison with minimum tilled or undisturbed soils (La Scala Jr. *et al.*, 2006; Zhang *et al.*, 2011a), no information is available regarding the effect of controlled traffic or strategic zone-tillage on temporal and spatial variations of soil CO_2 efflux.

The objective of this study was to characterize the effects of conventional tillage and strategic zone-tillage operations and site conditions (soil compaction, temperature and moisture) on soil CO_2 effluxes by means of in situ determinations of emissions in permanent and conventional bed planting systems. While most studies on tillage-induced soil CO_2 effluxes are focused on quantifying emissions just immediately after operations (hours) (e.g. Carbonell-Bojollo et al., 2011; Reicosky et al., 1997) or in the medium-term (days, weeks) (e.g. La Scala Jr. et al., 2006; Moussadek et al., 2011; Zhang et al., 2011a), the present study links both temporal scales. The limited experimentation on no-tilled irrigated systems under Mediterranean conditions is an additional justification for this paper.

3.2. Materials and Methods

3.2.1. Experimental site, tillage and traffic treatments and crop management

The present study was conducted at Alameda del Obispo experimental farm (latitude 37° 51' N, longitude 4° 47' W, altitude 110 m a.s.l.), Córdoba, Spain. The climate in the area is Mediterranean with mean annual temperature of 17.6 °C and mean annual rainfall of 536 mm, most of which concentrates between late autumn and early spring. Figure 12 shows daily temperature and precipitation (rainfall and irrigation) during the study. The soil is Typic Xerofluvent (Soil Survey Staff, 2010) or Eutric Fluvisol according to FAO system (IUSS, 2006), with loam texture of negligible shrinkage and without apparent restriction for root growth to 3 m depth. Particle-size distribution in the upper (0-0.15 m) soil layer consisted of 350 g kg^{-1} sand, 443 g kg^{-1} silt and 206 g kg^{-1} clay. The pH (1:2.5 water) and the electrical conductivity were 8.4 and 0.3 dS m^{-1}, respectively.

This study was conducted during 2011-2012 in a long-term trial set up in 2007 to compare permanent and conventional beds planting systems, combined with controlled traffic, in a maize (*Zea mays* L.)-cotton (*Gossypium hirsutum* L.) rotation with sprinkler irrigation (Boulal *et al.*, 2012). In 2010, a new treatment was added so that three different bed planting systems were compared since then: i) conventional beds with plant residues incorporated during soil preparation and beds formed every year (CB); ii) permanent beds with residues retained on the surface (PB); and, iii) a variant of PB in which subsoiling was practiced before sowing on those furrows that supported traffic (decompacted permanent bed planting system, DPB). Beds, both in PB and DPB, were never reshaped since they were formed in 2007.

The experimental plot covered 0.8 ha divided into three blocks. From 2007 to 2009, the blocks were sub-divided into two plots, each consisting of ten 0.85 m-spaced furrow/bed sets with either CB or PB established. In March 2010, the three plots devoted to PB treatment were subdivided and DPB was established in one side, occupying four furrow/bed sets. The remaining six furrow/bed sets continued as PB. The separation between two contiguous trafficked furrows (1.7 m) was imposed by the width of the tractor used (model *Kubota ME9000*). Traffic was controlled in the whole experiment and furrows with tractor wheel traffic (F+T) alternated with furrows without traffic (F-T). In CB, traffic was random during tillage for soil preparation but controlled after beds were formed. The number of wheel passes supported by F+T furrows during a cropping season varied across the experimental plot: sowing and slashing operations affected every single F+T but only some of these furrows were transited during the application of fertilizers and pesticides. Additionally, in DPB, F+T supported one extra wheel pass during the subsoiling operation. In this study, furrows with five wheel passes in PB and CB and six passes in DPB were selected as F+T furrows.

The experimental design was a split plot with three replicates. Main plots were represented by tillage or planting system treatments (CB, PB and DPB) and subplots by the presence of beds and furrows plus the control traffic treatment (Bed, F+T and F-T). Plot and crop management as well as details of irrigation practice during the study are shown in Table 3. Details of farming operations from 2007 to 2009 may be consulted in Boulal et al. (2012). In 2010 a maize crop was grown following the same management. This study was initiated in 2011 before any operation for cultivating the cotton crop corresponding to that year has taken place.

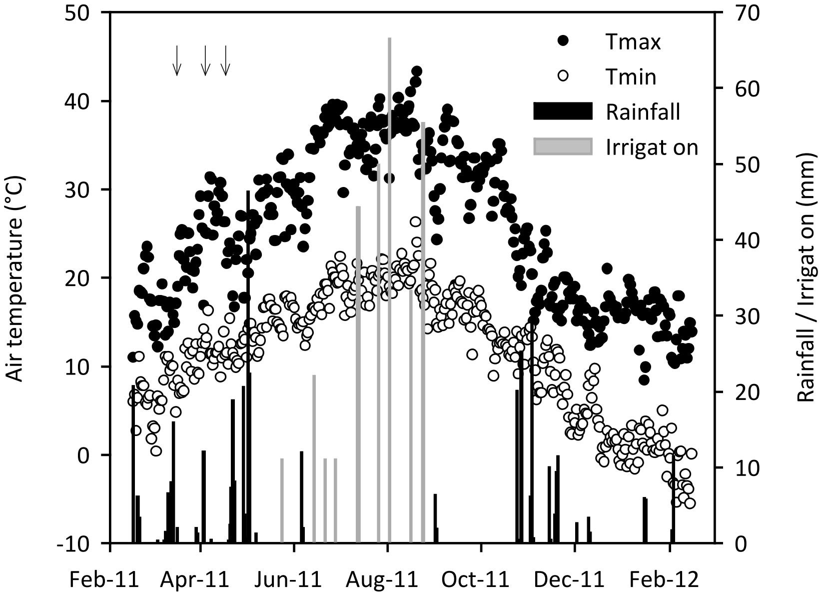

Figure 12. Daily maximum (Tmax) and minimum (Tmin) air temperature and precipitation (rainfall and irrigation) at the experimental site. Arrows indicate days on which subsoiling in the decompacted permanent-bed planting system, tillage sequence in the conventional bed planting system and sowing (in that order) were conducted.

3.2.2. Soil CO_2 efflux measurement

Soil CO_2 effluxes in the experimental plot were determined daily on 11 to 15 and 26 to 28 April and on 5, 6, 9, 10 and 11 May 2011, before and during soil preparation until crop sowing, as well as on 3 additional days, 25 May and 22 June 2011 and on 4 February 2012, for a total of 16 days. Round of measurements always started at 8:00 (solar time) in block 1 and ended in block 3. In nine measuring days, a second round followed starting at 11:00. In each round, effluxes were measured in one bed and two adjacent furrows (one with traffic, F+T, and one without traffic, F-T) at each elemental plot, i.e. in 27 positions (bed, F+T and F-T positions, by three planting systems by three blocks). During the tillage sequence in CB only this planting system was evaluated. Efflux readings lasted 150 seconds: one full round of 27 measurements took 90 minutes approximately. The day in which subsoiling took place in DPB (13 April 2011), CO_2 efflux was measured in the entire experiment immediately after the operation and three and six hours later (at 8:00, 11:00 and 14:00, respectively) as well as 24:00 later. During the tillage sequence for soil preparation in CB (27 April 2011), CO_2 efflux was measured in this planting system only immediately after each of the four operations (subsoiling, disc harrow, vibrocultivator and bed forming), i.e. at 9:00, 11:00, 14:00 and 16:00. The following day all 27 positions were measured at 8:00, as in the rest of the experiment.

Most measurements were made with a PVC cylindrical non-steady state (NSS) portable chamber (Rochette and Bertrand, 2008). The dimensions of the chamber (0.15 m in diameter, 0.34 m in height) allowed placing it on beds and furrows separately. The internal volume was ventilated with a type-computer fan and equipped with a thermistor to measure air temperature. A stainless steel vent tube 0.1 m long and 0.0048 m in diameter was placed at the top of the chamber to keep a pressure equilibrium between the inside of the chamber and ambient air while the chamber was closed. Leakage error was corrected according to Pérez-Priego et al. (2010). In late March 2011, a PVC ring (0.06 m height) was inserted into the soil surface (0.03 m depth) at each of the 27 evaluating positions in order to avoid soil disturbance and consequent interference on gas emission during positioning of the chamber. Rings remained in the soil during the study and they were removed only before wheel traffic if they were affected by this. Removed rings were reinserted on the same site or as closely as possible.

A second larger NSS portable chamber (1.2 m x 1.0 m base and 1.8 m height), constructed using the same materials and following a similar design than Pérez-Priego et al. (2010), was used to measure soil CO_2 effluxes in CB after the subsoiling, disking and vibrocultivator passes. The use of a chamber with a larger base was necessary due to the roughness of the soil surface created by the primary tillage (Reicosky *et al.*, 1997). After the beds were formed, CO_2 effluxes from the different positions were determined again by means of the smaller cylindrical chamber.

Both chambers were coupled to an infra-red gas analyser (IRGA, model *LI-COR LI-820*, Lincoln, NE, USA) to measure the variation of mol fraction of CO_2 (µmol mol^{-1}) in dry air over time. Air sampled was circulated from the chamber to the *LI-820* using a small pump, with an entering flux of 1 L min^{-1}. Dilution correction was not applied since CO_2 mol fraction in dry air was measured directly by circulating the air sampled through a desiccant tube before being drawn to the *LI-820*. The CO_2 efflux was calculated according to the equation in Rochette and Bertrand (2008).

3.2.3. Other soil measurements

Concurrently to CO_2 efflux measurements, soil temperature was measured at 0.025 and 0.07 m depth with a type-k soil thermocouple in bed and F-T in block 1 (i.e. in nine of 27 positions) during April and in block 1 and 3 (i.e. in 18 of 27 positions) for the rest of measuring dates except for the last two measurements in which soil temperature was measured in all positions in the three blocks. In 11 out of 16 days in which CO_2 efflux was measured, volumetric soil water content (SWC) for the top 0.15 and 0.60 m deep layers was also measured concurrently with a time domain reflectometry device (*MiniTrase System*, SoilMoisture Equipment Corp., Santa Barbara, CA, USA) in all 27 positions. Soil temperature and moisture were measured as close as possible to the site of CO_2 efflux measurement.

Soil samples were taken for determining SOC content in the 0-0.05, 0.05-0.10 and 0.10-0.25 m layers, in beds and their adjacent F+T and F-T furrows. Six samples were taken in each elemental plot to form a composite sample. Sampling took place on April 19, 2011. A second sampling was conducted in CB on June 6, 2011 (40 days after tillage). Samples were air-dried and passed through a 0.002 m sieve. SOC was determined according to Walkley and Black (1934).

In mid-May 2011, cone index (CI) (ASABE, 2009b) was measured with a recording soil penetrometer (*HINKA-2010* v1.0, Agrosap S.L., Córdoba, Spain) with a 0.01283 m diameter and 30° cone angle coupled to a portable computer. Soil CI was measured in five points per bed and adjacent F+T and F-T furrows at three sites per elemental plot. Cone index was measured in 0.005 m increments to a depth of 0.60 m at three sites per elemental plot. Soil water content was measured concurrently for the top 0.60 m soil with the TDR device. Cone indices were corrected to 18% of SWC following Busscher et al. (1997).

In early-June 2011, soil bulk density (ρ) was measured also in the centre of beds and adjacent furrows, at three sites per elemental plot, for the layers 0.05-0.10 and 0.20-0.25 m depths, using a 0.05 m diameter 0.05 m height cylinder. Samples were oven dried at 105 °C for 48 hours.

3.2.4. Data processing and statistical analysis

The average CO_2 efflux corresponding to a planting system was calculated by weighing the values obtained in each bed and furrow with/without traffic position according to the area that they represented (bed 50% and furrows 25% each one). The CO_2 effluxes from the different planting systems and positions at 8:00 were compared by using a mixed-model ANOVA applying nlme in R software (Pinheiro *et al.*, 2010). The measuring dates were divided into three periods: early and late dates in the study in which no tillage operation has taken place in any system, the date in which subsoiling has taken place in DPB and two following dates, and the period after soil preparation in CB. The model included the fixed factors *system* and *period* (in the systems comparison where weighed efflux values were used) or *system*, *position* and *period* (in the positions comparison), and the random effect *date* and *measuring ring*, as well as all the interactions. The most parsimonious model was selected in each of the two analyses: weighed and non-weighed values. Residuals were examined to confirm that all assumptions of ANOVA were met and a logarithmic transformation was used to improve normality assumption. In the two analyses the random effect was not significant and a linear model was applied. Additionally, comparisons of soil CO_2 effluxes among planting systems and positions were performed within every single round of measurement (generally for the values obtained in the 8:00 round unless indicated). When tillage and sowing operations took place, comparisons of effluxes belonging to different rounds of measurement were included in occasion of tillage and sowing operations, covering the ±24 hs period. Cumulative soil CO_2 efflux over time after tillage operations was calculated using numerical integration (trapezoidal rule) (Reicosky *et al.*, 1997). Means were separated by Tukey's HSD test with a significance level of 0.05 in all cases. Linear regression analyses were applied to determine the relationship between soil CO_2 efflux and soil temperature and SWC. In the case of soil temperature, the analysis considered only the blocks in which emissions and soil temperatures were measured concomitantly.

3.3. Results

3.3.1. Soil CO_2 efflux from planting systems

This section contains the results obtained at planting system level which were derived from weighting values from the furrows and the bed. CO_2 efflux differed among planting systems and these differences varied depending on tillage operations carried out at different periods during the study (Table 7). At the start of the study in early April 2011, prior to any tillage operation, average CO_2 efflux was 2.7 µmol m^{-2} s^{-1} and did not differ among planting systems (Figure 13a). Soil CO_2 flux in PB was relatively steady during the study being highest in late spring (5.1 µmol m^{-2} s^{-1}) and lowest at the end of the study in February 2012.

In DPB subsoiling took place on 13 April 2011 and CO_2 efflux rose to 17.8 µmol m^{-2} s^{-1} immediately after, exceeding significantly the efflux recorded the previous two days (Figure 13a). The efflux decreased drastically the same day (6.1 µmol m^{-2} s^{-1} at 11:00) and continued decreasing so that it did not differ significantly from PB and CB the following day.

In CB, CO_2 efflux increased significantly (up to 11 times) during the sequence of tillage operations carried out on 27 April 2011 (Figure 13b). Soil CO_2 efflux after the first operation, subsoiling (23.0 µmol m^{-2} s^{-1}), was lower than after the second operation, the disk harrow pass (32.2 µmol m^{-2} s^{-1}), but higher than the vibrocultivator pass (17.1 µmol m^{-2} s^{-1}) and bed formation (13.8 µmol m^{-2} s^{-1}), third and last operation in the sequence, respectively. The following morning, CO_2 efflux in CB had decreased to 7.7 µmol m^{-2} s^{-1} but still it was significantly higher (more than twice) than the efflux from PB or DPB and also than the efflux determined in CB before tillage (Figure 13b). Between 8 and 14 days later, differences in CO_2 efflux between CB and the other 2 planting systems were even higher: 11.0 vs. 3.2 µmol m^{-2} s^{-1} on average for measurements taken on 5, 6, 9, 10 and 11 May (although the differences was significant on 9 May only) (Figure 13c). These relatively higher soil CO_2 effluxes in CB had disappeared by 25 May 2011. In late May and June, measurements were carried out after plants emergence and, therefore, roots respiration was contributing to CO_2 efflux readings, probably in the same proportion in all planting systems as there were no differences in crop emergence date or above-ground biomass accumulation in mid-June among the three planting systems (data not shown).

Although sowing disturbed little soil, this operation resulted in an average increase of soil CO_2 efflux in PB and DPB of 4.6 µmol m^{-2} s^{-1} when compared with the emission measured the previous day at the same time (11:00) (differences were not significant). Contrary to PB and DPB, sowing did not increase soil CO_2 efflux in CB (data not shown).

Cumulative soil CO_2 efflux over time was calculated on data shown in Figure 13 for the 24 hs-period from subsoiling in DPB and tillage sequence in CB as well as for the period comprised between 5 and 9 May 2011 (Table 8). The lack of measurements of CO_2 efflux in PB and DPB during tillage in CB from 9:00 to 18:00 on 27 April 2007 was complemented by using estimated values obtained from the soil temperature measured at that time and using the relationship obtained between those two parameters (see Section 3.3). Compared to the system where the soil was not disturbed, the accumulated soil CO_2 was 5 and 4 times greater in DPB after subsoiling and in CB after soil preparation, respectively. The cumulative CO_2 emitted from CB was also significantly higher than in the other two systems during the dates following its soil preparation. The accumulated CO_2 recorded by the integration procedure (0.7 g CO_2 m^{-2} h^{-1} as a grand mean among periods and systems) was of a similar order of magnitude than that obtained by Álvaro-Fuentes et al. (2007). Nevertheless, and as pointed out by these authors, the fluctuations of effluxes between measurements were not considered and therefore, the obtained values should be used only for relative comparisons.

Table 7. ANOVA to compare planting systems (weighed values) and bed-furrow positions (single values) in terms of CO_2 efflux.

	Source	DF	SS	MS	F value	Prob. (> F)
a) System scale (after weighting values)	System	2	5.39	2.69	8.20	0.000
	Period	2	8.39	4.20	12.78	0.000
	Block	2	0.49	0.25	0.75	0.473
	System*Period	4	9.87	2.47	7.51	0.000
b) Single positions scale	System	2	5.21	2.60	7.70	0.001
	Position	2	2.94	1.47	4.34	0.014
	Period	2	15.01	7.51	22.19	0.000
	Block	2	0.86	0.43	1.28	0.280
	System*Position	4	42.37	10.59	31.32	0.000
	System*Period	4	7.47	1.87	5.52	0.000
	Position*Period	4	8.96	2.24	6.63	0.000
	System*Position*Period	8	9.06	1.13	3.35	0.001

DF: degrees of freedom; SS: sum of squares; MS: mean square.

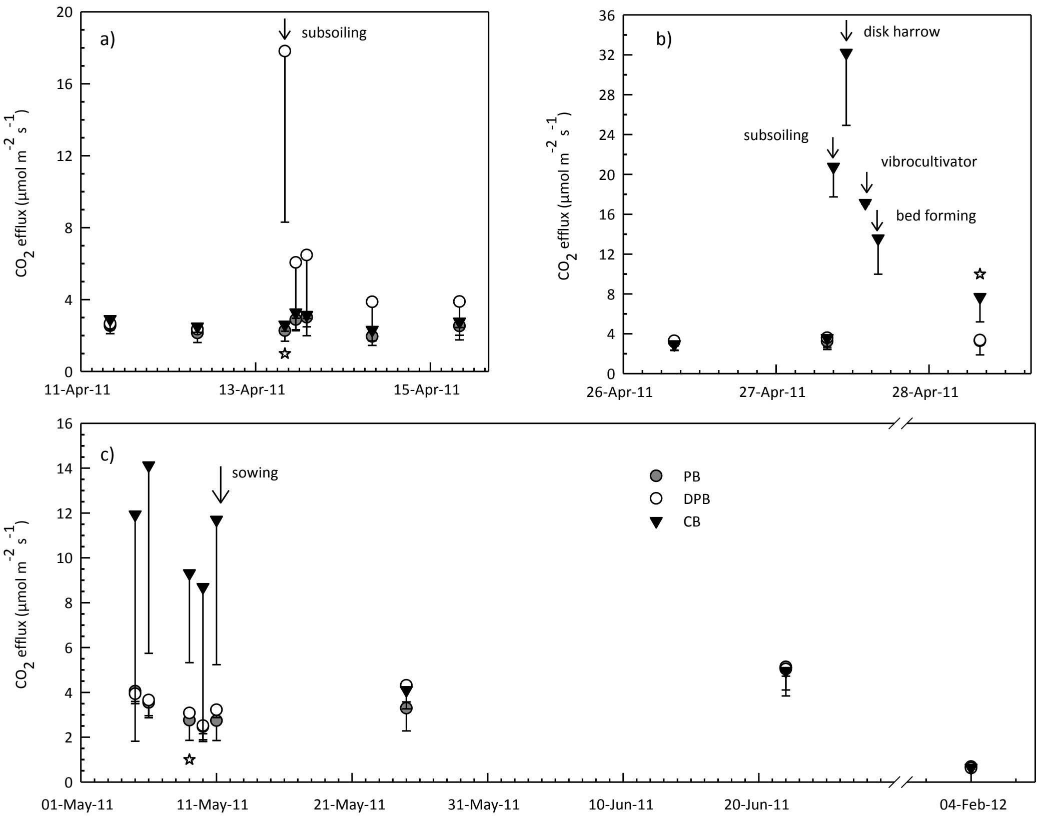

Figure 13. Soil CO_2 efflux around subsoiling in DPB (a) and tillage sequence in CB (b), as well as soil CO_2 effluxes at 8:00 for each measurement date in the rest of the study (c). The arrow in subfigure c indicates the day on which sowing was conducted. Error bar indicates half standard deviation. Asterisk indicates significant differences among treatments at 5%.

Table 8. Cumulative CO_2 efflux (g m^{-2}) during the time around subsoiling in DPB (11-15 April 2011), soil preparation in CB (26-28 April 2011) and dates following soil preparation in CB (5-11 May 2011).

Period (from 8:00 to 8:00)	Accumulated CO_2 efflux (g m^{-2})		
	PB	DPB	CB
13-14 April 2011	8 b	43 a	10 b
27-28 April 2011	13 a	14 a	53 a
5-11 May 2011	73 b	78 b	268 a

3.3.2. Soil CO_2 efflux from bed and furrows

The emissions of CO_2 differed among bed/furrows positions, planting systems and periods of measurements associated to tillage operations (Table 7). As all the interactions among these factors were significant, the efflux of CO_2 from the different positions is presented by planting system (Figure 14). Soil CO_2 efflux measured the same day in bed and furrows in PB and bed and F-T in DPB, i.e. undisturbed sites, were similar throughout the study (Figure 14a and 14b). The observed rise in DPB after subsoiling F+T furrows was the result of an increase in soil CO_2 effluxes from these furrows only: 65.9 µmol m^{-2} s^{-1}, the highest registered during the study. Although the efflux decreased drastically the same day, it remained more than twice the efflux in bed and F-T until June (6.8 and 2.8 µmol m^{-2} s^{-1}, in F+T and in bed/F-T, respectively, on average for this period) and the tendency remained until February 2012 (Figure 14b). Already at the start of the study, CO_2 efflux in DPB was higher from F+T soil than from the other two positions. Furthermore, F+T in DPB released significantly more CO_2 than the F+T in PB for the 69% of the measurements in the study, even before subsoiling (11 and 12 April, 2011) and in February 2012.

In CB, soil CO_2 efflux was higher from beds than from furrows once beds were formed, particularly between 8 and 13 days later (Figure 14c): average soil CO_2 efflux for the period between 5 and 11 May 2011 was 18.8 µmol m^{-2} s^{-1} in the bed compared to 3.5 µmol m^{-2} s^{-1} in the furrows. Differences were reduced by late May but the trend remained and CO_2 efflux was significantly higher in beds than in furrows in June 2011 and February 2012 (1.8 and 1.6 times, respectively). Soil CO_2 efflux from F+T and F-T CB was similar in all measurements during the study, furthermore, these values did not differ from those measured in undisturbed soil (beds and furrows in PB and beds and untrafficked furrows in DPB), even the day after the tillage sequence in CB (Figure 14).

Soil CO_2 effluxes from beds increased (although not significantly) more than four times in PB and DPB one hour after the cotton sowing operation (carried out on 11 May at 10:00) in relation to 24 hours before; conversely, the effluxes decreased by 14% in CB. The sowing-induced effect on soil CO_2 effluxes can be also observed by comparing the increases in emissions from 8:00 to 11:00, before and after sowing. Average CO_2 efflux the two previous days to sowing increased around 1.4 times in PB and DPB and 1.3 times in CB from 8:00 to 11:00. However, the morning on which the sowing was carried out, the increase was of about 5.3 times in PB and DPB, significantly higher than the increase observed the two previous days, while effluxes decreased by 14% in CB (data not shown).

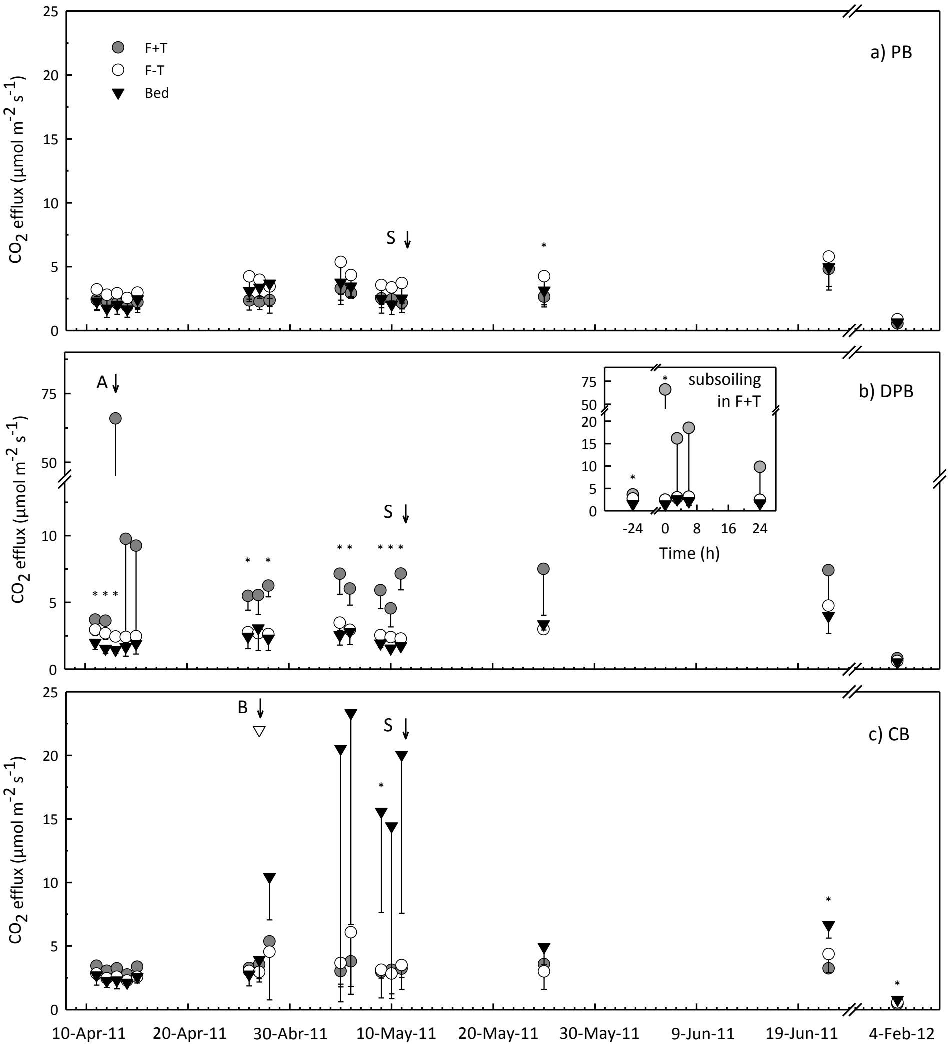

Figure 14. Soil CO_2 efflux at 8:00 from bed (solid triangle), furrows with traffic (F+T, solid circles) and furrows without traffic (F-T, open circles) in permanent bed planting (PB), decompacted permanent bed planting (DPB) and conventional bed planting (CB). Arrows indicate days on which subsoiling in DPB (A), tillage sequence in CB (B) and sowing (S) in all planting treatments were conducted. White triangle in CB Figure represents average CO_2 efflux for the whole sequence of tillage in CB performed from 9:00 to 16:00. Subfigure shows the short-term CO_2 efflux around subsoiling operation. Error bar indicates half standard deviation. Asterisk indicates significant differences among positions at 5%.

3.3.3. Complementary soil parameters

Soil CO_2 efflux for day, block, time of measuring (early and late morning) and planting systems in relation to soil temperature at 0.07 m depth is shown in Figure 15. A significant relationship between both parameters could be established by considering all the cases as a single set, except those recorded in DPB the day when subsoiling was carried out and those recorded in CB after the tillage sequence and until sowing: soil CO_2 efflux (μmol m^{-2} s^{-1}) = 0.16 μmol m^{-2} s^{-1} °C^{-1} * T_7 °C - 0.41 μmol m^{-2} s^{-1}; $R^2 = 0.62$; $p < 0.001$ (a similar relationship was obtained for soil temperature at 0.025 m depth; slope = 0.15 μmol m^{-2} s^{-1} °C^{-1}; $R^2 = 0.59$; $p < 0.001$). Thus, an increase of 10 °C in T_7 would result in an increase of 1.6 μmol m^{-2} s^{-1} provided the soil is not disturbed by tillage operations. CO_2 efflux and soil temperature also increased between the first and third measured blocks within complete rounds. Average CO_2 efflux and soil temperature at 0.07 m depth (excluding the same days than in Figure 15) were 3.2 and 4.1 μmol m^{-2} s^{-1} and 23.2 and 25.2 °C, in block 1 and 3 respectively.

Similar proportional differences were observed between measurements carried out early and late the same morning (data not shown). The values of soil temperature and CO_2 recorded after crop emergence fitted the relationship because cotton roots respiration was still small.

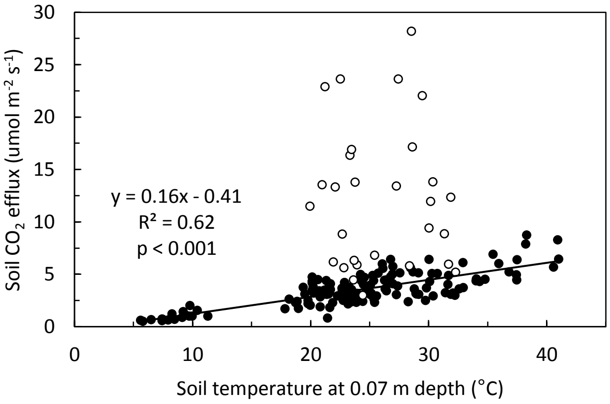

Figure 15. Soil CO_2 efflux for day, block, time of measuring (early and late morning) and planting systems in relation to soil temperature at 0.07 m depth during the entire experiment. Open symbols correspond to measurements carried out in DPB and CB after tillage operations. The regression belongs to solid symbols.

The release of soil CO_2 was dependent on soil moisture after the heavy rainfalls between 29 April and 3 May 2011 (93.7 mm accumulated). During the subsequent drying process (5-11 May 2011 period), CO_2 efflux from soil in PB and DPB decreased in time as soil got dryer (Figure 16) in spite of getting hotter. Effluxes in CB tended to decrease with moisture but the relationship in this case was not significant. On the other hand, and taking into account the entire experiment, the driest conditions coincided with the coolest and least soil effluxes (February 2012).

Average SWC tended to be lower in the bed compared to furrows, particularly in the top 0.15 m layer and in CB: 23% less in PB and DPB and 32% less in CB for the 0-0.15 m soil layer, and 14% in the 3 systems for the 0-0.6 m layer (data not shown).

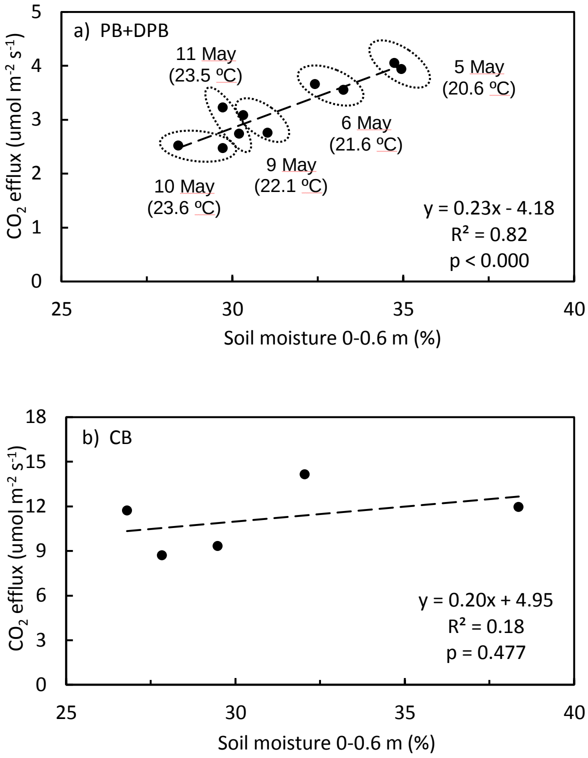

Figure 16. Soil CO_2 efflux measured after a rainfall event (between May 5 and 11) in PB+DPB and CB in relation to soil moisture. The average soil temperature (blocks 1 and 3) is indicated between parentheses.

The content of SOC varied with depth, position and planting system (Table 9). SOC accumulated in the 0.05 m top soil in relation with deeper soil (0.1-0.25 m), particularly in furrows of PB and DPB but also in furrows of CB before the tillage sequence. In PB and

DPB, the content of SOC tended to be higher in furrows than in beds, particularly in the 0.05 m top soil. Contrarily, the content of SOC did not differ among positions in CB. Differences among planting systems were found only in the 0-0.05 m soil layer, where CB hold less SOC than PB and DPB in F-T and less SOC than PB in F+T. Despite the lack of significant differences comparing PB with DPB, the content of SOC reduced by 22% in the latter in the 0-0.05 m soil layer of furrows with traffic. The tillage sequence and bed forming in CB penalized its SOC content, with significant reductions in the entire profile of F-T and only in the 0.1-0.25 m soil layer of F+T.

Table 9. Soil organic carbon content (%) in the untrafficked (F-T) and trafficked (F+T) furrows and in the bed of the permanent (PB) and decompacted permanent (DPB) beds planting systems and in the conventional beds planting system before (CB) and after (CBt) tillage operations and bed forming.

Soil layer (m)	Planting system	Position		
		F-T	Bed	F+T
0.00 - 0.05	PB	1.6 abA	1.1 bA	1.8 aA
	DPB	1.5 aA	1.0 bA	1.4 aAB
	CB	1.0 aB	1.1 aA	1.1 aB
	CBt	0.7 a*	0.8 a	0.7 a
0.05 - 0.10	PB	1.0 aA	0.8 bA	0.9 abA
	DPB	1.0 aA	0.8 aA	0.9 aA
	CB	0.8 aA	1.0 aA	0.9 aA
	CBt	0.7 a*	0.8 a	0.6 a
0.20 - 0.25	PB	0.6 bA	0.7 aA	0.6 bA
	DPB	0.6 aA	0.6 aA	0.6 aA
	CB	0.6 aA	0.8 aA	0.6 aA
	CBt	0.4 a*	0.6 a	0.4 a*

Values with the same lowercase letter within a row and values with the same uppercase letter within a soil layer and position are not different at 0.05 of significant level. The asterisk indicates that the SOC content in CB after tillage operations, i.e., CBt, is significantly lower than before tillage.

Cone index was measured in mid-May after all operations have been carried out, including sowing. Results are presented for the top 0.2 m (Table 10) as positions did not differed below that depth except in the bed in CB, on which soil offered the least penetration resistance down to 0.6 m. In PB, CI was significantly higher in F+T compared to F-T, similarly to CB at the 0.1-0.2 m soil layer. The tendency was the opposite in DPB, reflecting the effect of the subsoiling operation. Cone indices tended to be lower in the bed relative to furrows in the three planting systems. By comparing planting systems, the lowest CI in trafficked furrows was that in DPB as well as the lowest cone indices in beds and untrafficked furrows were those in CB. Bulk density in PB and DPB did not show any trend but, in CB, soil was significantly more compacted in furrows than in beds (Table 10).

Table 10. Soil bulk density and cone index in the untrafficked (F-T) and trafficked (F+T) furrows and in the bed of the permanent (PB) and decompacted permanent (DPB) beds systems planting and in the conventional beds planting system before (CB). The cone indices were adjusted to the same SWC (18%).

Planting system	Soil bulk density (g cm^{-3})				Soil cone index (MPa)			
	Soil layer (m)	Position			Soil layer (m)	Position		
		F-T	Bed	F+T		F-T	Bed	F+T
PB	0.05 - 0.10	1.46 aB	1.45 aB	1.52 aA	0.00 - 0.10	2.8 bB	2.4 bA	3.6 aA
	0.20 - 0.25	1.56 aA	1.59 aA	1.57 aA	0.10 - 0.20	3.2 bA	2.3 cB	3.9 aA
DPB	0.05 - 0.10	1.42 aB	1.38 aB	1.47 aA	0.00 - 0.10	2.5 aB	2.4 aA	1.7 bA
	0.20 - 0.25	1.55 aA	1.58 aA	1.57 aA	0.10 - 0.20	2.8 aA	2.2 bA	1.7 cA
CB	0.05 - 0.10	1.58 aA	1.39 bA	1.59 aA	0.00 - 0.10	2.0 aB	1.4 bA	2.1 aB
	0.20 - 0.25	1.59 aA	1.48 aA	1.56 aA	0.10 - 0.20	2.4 bA	1.3 cA	2.7 aA

3.4. Discussion

Relative increases in soil CO$_2$ effluxes (up to 6 and 11 times compared to previous day in DPB and CB, respectively) (Figure 13a and 13b) were of similar order of magnitude to those determined in rainfed cereal based systems by Carbonell-Bojollo et al. (2011) in southern Spain, by Álvaro-Fuentes et al. (2007) and Morell et al. (2010) in northeastern Spain, and by Moussadek et al. (2011) in northern Morocco (no study on irrigated systems available). In absolute terms, peak values of CO_2 efflux determined in this study were consistent with those reported after mouldboard ploughing in cereal-based systems in northern and southern Spain (Álvaro-Fuentes *et al.*, 2007; López-Garrido *et al.*, 2009) and in grasslands in Southeast Ireland (Willems *et al.*, 2011) for different soil types (including Xerofluvents). Peaks of CO_2 efflux determined immediately after tillage are considered an abrupt expulsion of this gas previously accumulated into the soil structure and released to the atmosphere after changing the soil physical characteristics with the labour (Reicosky *et al.*, 1997). Therefore, the peak values of soil CO_2 efflux depend on the volume of soil disturbed by the tillage operation and the concentration of CO_2 in that portion of soil (Reicosky and Lindstrom, 1993; Álvaro-Fuentes *et al.*, 2007).

Three hours after recording the maximum values in these *degassing* processes [a term used by Rochette and Angers (1999)], a reduction in CO_2 effluxes was observed in DPB (60% lower) and CB (47% lower), in agreement with other authors for different conditions (e.g. Reicosky et al., 1997; Morell et al., 2010). In CB, the reduction continued throughout the day, even though two more soil disturbing events (vibrocultivator pass and bed forming) were carried out between the peak recorded at 11:00 after the disk pass and the final reading at 16:00 on that day. The CO_2 concentration gradient between the tilled soil and the atmosphere was reduced enough to hamper a peak of similar magnitude. The larger CO_2 efflux recorded after the disk pass rather than after subsoiling (the second operation and the first operation, respectively), was related to the degree of soil disturbance corresponding to each operation since subsoiling affected the furrows with traffic only, whereas disking disturbed the entire soil. The efflux of CO_2 recorded immediately after disking could also include CO_2 produced *de novo* from rapid degradation of most labile organic compounds that became available to microbial activity in the portion of soil previously affected by subsoiling, as shown by Wuest et al. (2003). Despite the scatter associated with degassing processes (Figure 13), the estimation of cumulative CO_2 allowed to differentiate significant increments in planting systems after tillage operations.

The magnitude of *degassings* observed in beds in PB and DPB as a consequence of cotton sowing operation during the morning on 11 May agree with those recorded be Carbonell-Bojollo et al. (2011) after sunflower (*Helianthus annuus* L.) and pea (*Pisum arvense* L.) crops sowings. However, only intraday increases in CO_2 effluxes due to sowing can be concluded from results in Carbonell-Bojollo et al. (2011) with the associated risk of confounding effects in relation with temperature (data of effluxes for the previous 24 hours is not reported in such research). In this sense, sowing-induced increases in soil CO_2 effluxes observed by Carbonell-Bojollo et al. (2011) in January and December 2007 agree with those observed in this and other studies (e.g. Nakadai et al., 2002) without performing any soil disturbance, i.e. due only to changes in diurnal conditions (air/soil temperature). The reduction in CO_2 efflux detected in our study after sowing in CB may be due to a slight effect of compaction by the closure discs of the planter dominating on the disaggregation effect of its harrows, both effects operating on a previously highly loose soil. The sowing promoted the effluxes in PB and DPB probably due to the opposite reason: a highly consolidated soil that was disturbed by the drill boots. Nevertheless, despite the reduction in CO_2 emissions caused by sowing in CB beds, effluxes remained higher than in PB and DPB.

Effluxes in CB significantly increased 12 days after the tillage sequence (Figure 13c). This period, in which the soil CO_2 emitted in CB exceeded four times the output from PB and DPB, was characterized by numerous rainfall events, as a result of which SWC reached its highest value also (data not shown). Other researches (Dao, 1998; Alvarez *et al.*, 2001; La Scala Jr. *et al.*, 2006; Zhang *et al.*, 2011a) have indicated certain delay (from six to 30 days) between soil tillage and maximum efflux of soil CO_2. In some cases, the lag period ended when rainfall occurred. These studies (in particular the results achieved by Zhang et al. [2011a], where maximum values of soil CO_2 efflux were recorded not after the first but after subsequent rainfall events from tillage) suggest that, besides soil moisture, time is required for the organisms to colonize and decompose plant residues buried by tillage operations. Laboratory studies on soil incubation have demonstrated the importance of soil moisture and the moistening processes on CO_2 releases (Liebig *et al.*, 1995; Lee *et al.*, 2009), which are linked to microbial activity (Orchard and Cook, 1983; Franzluebbers, 1999). At field experiments level, Zhang et al. (2011b) measured CO_2 effluxes during two years and estimated a period affected by tillage which lasted for one month after labours. In our case, we have limited measurements to determine the length of this phase but in 25 May 2011, i.e. 28 days after the tillage sequence for bed forming in CB, there were no differences in soil CO_2 efflux between CB and the untilled soil (Figure 13c), what agrees with the mouldboard ploughing-induced timescale for increased effluxes in different regions of Europe reported in Eugster et al. (2010).

Soil CO_2 efflux was related to soil temperature (slope = 0.15 and 0.16 $\mu mol\ m^{-2}\ s^{-1}\ °C^{-1}$ for temperature measured at 0.025 and 0.07 m, respectively) unless tillage was recent (Figure 15); the sensitivity of soil CO_2 effluxes to soil temperature would be increased under the new soil conditions imposed as a consequence of tillage (Zhang *et al.*, 2011a) but the scope of the present study did not cover the determination of such particular relationship. In this sense, and sometime after tillage and bed forming in CB, soil CO_2 effluxes from this soil also fitted the relationships, in agreement with Zhang et al. (2011b). The response to soil temperature determined for CO_2 efflux in our study agrees with that reported by Morell et al. (2010) for a non-tilled soil (slope = 0.15 μmol m^{-2} s^{-1} $°C^{-1}$), for a similar range of temperature (between 10.3 and 24.2 °C, at 0.05 m depth) and soil gravimetric moisture (between 16 and 23%, for the 0-0.05 m layer).

At field scale, the influence of SWC on CO_2 effluxes under relatively steady conditions can be studied after a rainfall event, during soil drying. We observed a reduction in CO_2 efflux during the drying process in PB and DPB (Figure 16), in agreement with Morell et al. (2010) study on post rainfall events for no-tilled soil in northern Spain. Zhang et al. (2011a) also obtained a reduction in CO_2 effluxes with SWC for a similar range in SWC and soil temperature. On the other hand, as occurred when trying to establish the relationship between soil temperature and CO_2 efflux, no clear effect was observed in CB during the drying cycle after the rainfall event because it occurred eight to 14 days after tillage, when CO_2 efflux was still high. When intensive tillage took place recently, the weather and soil interact in a complex way on the production and emission of CO_2, which may explain these difficulties to establish possible relationships between site conditions and soil CO_2 effluxes (Reicosky *et al.*, 2008).

The drying cycle studied in this work together with others conducted in different regions and climate conditions (e.g. Casals et al., 2011; Morell et al., 2010; Wichern et al., 2004) have shown that soil moisture is critical on CO_2 emissions of heterotrophic nature under different temperature conditions. For this reason, the lowest value of CO_2 efflux determined in the entire experiment, the ones recorded in February 2012, may have been due not only to the cold conditions but also to the low moisture content of soil, that was of 23% at the 0-0.6 m soil layer.

Differences in effluxes of CO_2 among planting systems (Figure 13) are better understood considering the measurements from furrows and beds separately (Figure 14). The high CO_2 effluxes from CB after soil preparation derived mostly from bed soil, as also reported by Müller et al. (2009a). Similarly, in the case of DPB, the higher effluxes in this planting system after subsoiling derived mostly from F+T, the furrows were the operation took place. The subsoiling-induced CO_2 efflux in DPB was more than double the peak resulting from subsoiling in CB for a similar soil disturbance or from the disk harrow pass with full disturbance.

According to CI and ρ determinations, soil in the bed in CB was less compacted than in both furrows (Table 10), as reported in other studies on ridged soils (Benjamin *et al.*, 1990; Liebig *et al.*, 1993). Both the wheel traffic and the pressure of the harrows used to form the beds would have contributed to compact the soil. In this sense, Heard et al.

(1988) determined that the soil air-filled porosity of the bed in different types of ridged soils was higher not only compared to their adjacent furrows, but also when compared to soils under other regimes of tillage (e.g. mouldboard ploughing, chisel ploughing or no-tillage). Taking into account that small decreases in soil macroporosity can induce a large decline of air permeability and diffusivity (Ball and Robertson, 1994), it is reasonable that the recently formed beds in CB had more favourable conditions for gas movement relative to furrows. With time, the soil in the beds reconsolidated presumably as a result of rainfall and irrigation events (Reicosky and Archer, 2007) and CO_2 effluxes were reduced as observed from 11 to 25 May 2011, i.e. about one month after tillage sequence and bed forming (Figure 14c). Müller et al. (2009a,b) also reported an increase in soil bed ρ along with a decrease of CO_2 effluxes few months after beds formation. Nevertheless, significantly higher CO_2 effluxes were still observed in beds in CB in June 2011 and February 2012. Soil conditions were more favourable to CO_2 efflux in beds compared to furrows; in particular, CI values indicated a more loosened soil in beds relative to furrows still in December 2011, i.e., eight months after tillage (data not shown). Long term effects of tillage operations on soil loosening and other physical properties like soil macroporosity have been observed in other tillage studies (Carter, 1988).

In DPB, CO_2 efflux from F+T was higher than from F-T and bed during most of the study (Figure 14b) as well as from F+T in PB during the entire experiment. Differences in CO_2 efflux in April 2011 would be the result of subsoiling conducted in March 2010; similarly, measurements on February 2012 would be the result of subsoiling conducted in April 2011. The higher CO_2 effluxes from F+T relative to F-T in DPB, as well as to F+T in PB, were consistent with the lower CI values in F+T furrows in DPB in May 2011 (Table 10), and also before and after subsoiling (data not shown). Tractor wheels were wider than the soil band loosened by subsoiling. This operation displaced a small quantity of soil to the borders of the loosened band and probably absorbed most of the tractor weight compaction. Intermediate CI measurements between the centre of furrows and beds are needed to confirm this. As discussed in relation with beds in CB, the sustained effect of soil loosening by subsoiling in DPB would facilitate CO_2 release (and O_2 influx), explaining in part the higher gas effluxes from F+T during the year (April 2011 to February 2012). Lower CI due to subsoiling has been observed also after one year of carrying out the operation (Pierce *et al.*, 1992). Subsoiling does not invert soil but still disturbs it vertically, enough for releasing additional amounts of CO_2 in comparison with the undisturbed positions (bed and F-T) in this planting system. This agrees with the lower SOC content in the top 0-0.05 m layer in F+T in DPB compared with the unsubsoiled F+T in PB. The loss of organic carbon in response to soil disturbance has been reported for rainfed annual crops based systems in the region (López-Fando and Pardo, 2011; López-Garrido *et al.*, 2012).

3.5. Conclusions

Measurements of soil CO_2 effluxes conducted in situ allowed us to characterize the effect of tillage operations and traffic treatments on emissions, as well as to determine that CO_2 emissions were positively related with soil temperature and moisture except whether tillage was recently performed.

Tillage operations carried out on irrigated permanent and conventional bed planting systems abrupt emissions of CO_2 of similar magnitude to those reported for rainfed conditions. In the case of CB, few days after tillage operations, high effluxes were observed again in beds but not in furrows where soil compaction took place during the harrowing for beds shaping. In regard with DPB, spatial differences were observed after the subsoiling operation in F+T that increased soil CO_2 effluxes from it relative to the bed and F-T during most of the study in spite of the subsequent traffic. In fact, emissions from F+T of DPB were higher since the beginning of the study, indicating a residual effect of the subsoiling operation conducted in the spring in 2010. Most probably, the borders of the loosened band were still highly compacted and were able to hold most of the tractor weight but it needs to be confirmed. The high CO_2 efflux in the subsoiled furrow agrees with its lower SOC content compared with furrows that were not disturbed in PB.

Controlled traffic treatment had no effect on CO_2 emissions from furrows, neither in PB nor in CB (furrows formed in 2007 and in late April 2011, respectively). A certain threshold of soil compaction can be exceeded in the furrows during the harrowing for beds shaping, so that subsequent traffic has no effect on soil surface properties regarding gas efflux.

Further research is required for characterizing the effect of soil temperature and moisture on soil CO_2 emissions, and irrigation could play a key role on that. However, whether a stand of plants is present, the effluxes recorded will contain CO_2 resulted from autotrophic respiration, what should be considered to avoid confounding effects in studies conducted during irrigation periods. Finally, full daily curves rather than punctual measurements of CO_2 effluxes will facilitate studying the interaction of soil microclimatic conditions on gas emission as well as the calculation of the accumulated CO_2 efflux during any studied period.

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Chapter 4 - Catchment scale hydrology of an irrigated cropping system under soil conservation practices

ABSTRACT

Water erosion is a pressing environmental problem caused and suffered by agriculture in Mediterranean environments. Soil conservation practices can contribute to alleviate this problem. Soil conservation research in experimental plots overlooks runoff and erosion scale effects. Catchment studies should therefore complement small scale research. In this study, we present a hydrological station to measure runoff, sediments and agrochemical losses from a catchment in a commercial farm in southern Spain, where a package of soil conservation practices are an essential part of the farming system. The catchment has 27.42 ha devoted to irrigated annual crops with maize-cotton-wheat as primary rotation. Mean annual rainfall runoff coefficient was 0.14 and mean annual soil loss was 2.4 Mg ha^{-1} year^{-1}. Irrigation contributed with 40% of the crop water supply but the amount of runoff and sediment yield that it generated was negligible. The discussion underlines the effect of preceding soil moisture as determinant of rainfall runoff, the great effect of crop residues covering the soil surface on the reduction of sediment losses, the interest of growing cover/catch crops during autumn and early winter to enhance soil protection, and the role of irrigation facilitating these conservation practices.

4.1. Introduction

Water erosion of agricultural soil is probably the most serious environmental problem that southern Spain agriculture is facing. There have been major efforts in quantifying olive orchard soil losses at catchment scale (Taguas *et al.*, 2009, 2010, 2013) and in comparing, at mini plot scale, olive orchard soil conservation practices (Francia Martínez *et al.*, 2006; Gómez *et al.*, 2009). Less has been done for annual crops, for which the development of soil conservation practices has been very modest (MAGRAMA, 2012).

The introduction of innovative soil conservation practices by a farmer Córdoba province (Calleja *et al.*, 2008) has brought the opportunity to assess them in irrigated annual crops. The set of practices includes semi-permanent beds, residues retention in furrows, reduced tillage, controlled traffic, and crop rotation. The advantages of this system (infiltration enhancement and reduction of runoff and soil losses) were evaluated by Boulal *et al.* (2011a,b) in an experimental field where the hydrological processes could be controlled.

However, the scale effects on runoff and erosion assessment (Leys *et al.*, 2010) recommend the evaluation of the system in its natural condition, which requires measurements at catchment scale.

Studies at catchment scale are based on monitoring factors that may affect the hydrology of the cropping system while measuring flows at the catchment outlet, with the aim of determining and quantifying cause-effect relationships. There are fixed factors, such as catchment soil type, size and topography; factors, as rainfall, that vary in time but cannot be controlled; and management factors, such as crop rotation, soil tillage, crop residues maintenance, and irrigation. For example, Casalí *et al.* (2008) and Giménez *et al.* (2012) evaluated two agricultural catchments in northern Spain that behaved differently due to differences in morphology, topography, and amount of stream channel vegetation. Latron and Gallart (2007) highlighted the importance of preceding rainfall on the hydrological response of a catchment in the Pyrenees, distinguishing between dry, wetting-up and wet periods. Crop, tillage system, and residues cover also have been reported as management factors that influence the amount of runoff and soil loss from agricultural land (Carroll *et al.*, 1997; Nunes *et al.*, 2011; Gellis, 2013).

In Mediterranean environments, irrigation enhances productivity and allows growing crops that otherwise would be unviable. From the soil conservation perspective, irrigation can induce erosion (Carter, 1990), particularly towards the outer end of centre pivot wings (Howell *et al.*, 2002), but also the enhanced productivity contributes to greater amount of crop residues that may be used to retain water and soil. Catchment scale studies allow comparative assessments of the effects of rainfall and irrigation on soil conservation as they are the preferred domain for irrigation performance assessments (Isidoro *et al.*, 2004; Barros *et al.*, 2011).

The objective of the present study was to discern, at catchment scale, the factors that are more relevant in determining runoff and soil loss in an irrigated, annual-crops cropping system that uses soil conservation practices. A pilot gauging-station was designed and tested as part of the assessment, with the additional purpose of measuring return flows and assessing water usage using the catchment as domain of analysis.

4.2. Materials and methods

4.2.1. The study catchment and the farming system

The study site is located in Fuente Palmera, southern Spain (latitude 37° 44’ N, longitude 5° 09’ W, altitude 126 m a.s.l.). Climate is typically Mediterranean (Figure 17). Average annual rainfall is 630 mm, concentrated from autumn to spring. Average temperature varies from 10 °C in January to 28 °C in August. Average annual reference evapotranspiration (ET_o) is 1315 mm, ranging from 1 mm day^{-1} in January to 7 mm day^{-1} in July.

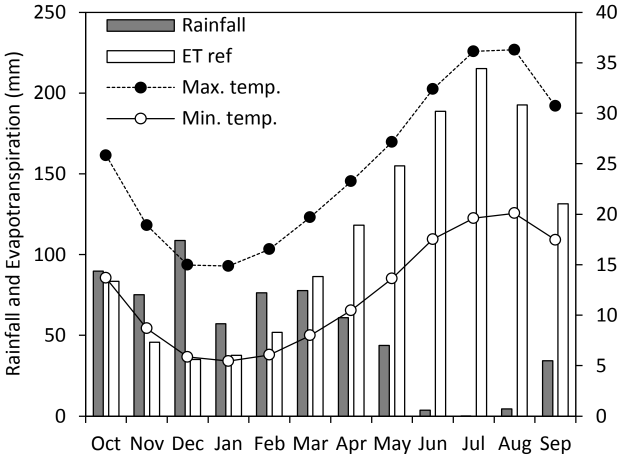

Figure 17. Mean monthly rainfall, reference evapotranspiration and daily minimum and maximum temperatures in the catchment (period 2000 to 2013).

Limits and topography of the catchment were determined from a topography survey done with a total station. The catchment covers an area of 27.42 ha devoted to irrigated annual crops. Its limits are watershed division lines and artificial barriers like roads or shallow drainage ditches (Figure 18). The catchment consists of two plots (Plot I and Plot II), both irrigated by means of a centre pivot. Solid set sprinklers irrigate the small areas of both plots that are not reached by the centre pivot. Plot I is entirely within the basin occupying 21.17 ha. Only a portion of Plot II is within the basin, occupying 6.25 ha (Figure 18). Plot II drains into the semi-permanent channel crossing Plot I, through a culvert under the road that separates both plots (Figure 18). The mean slope is 6% and soils are *Typic Calcixerept* and *Typic Haploxerert* (Soil Survey Staff, 2010). Different zones in terms of topography and soil characteristics were distinguished across the catchment (Boulal and Gómez-Macpherson, 2010). Among these zones, slopes range from 0-5 to 15-30% and soil organic carbon content averages 1%. Another feature of the soil is the presence of rolling stones, on average 12% of the 0-0.3 m top soil layer. Soil texture was determined at the six zones distinguished by Boulal and Gómez-Macpherson (2010); soil depth is greater than 3 m. Field capacity and wilting point were estimated from soil texture (Allen *et al.*, 1998).

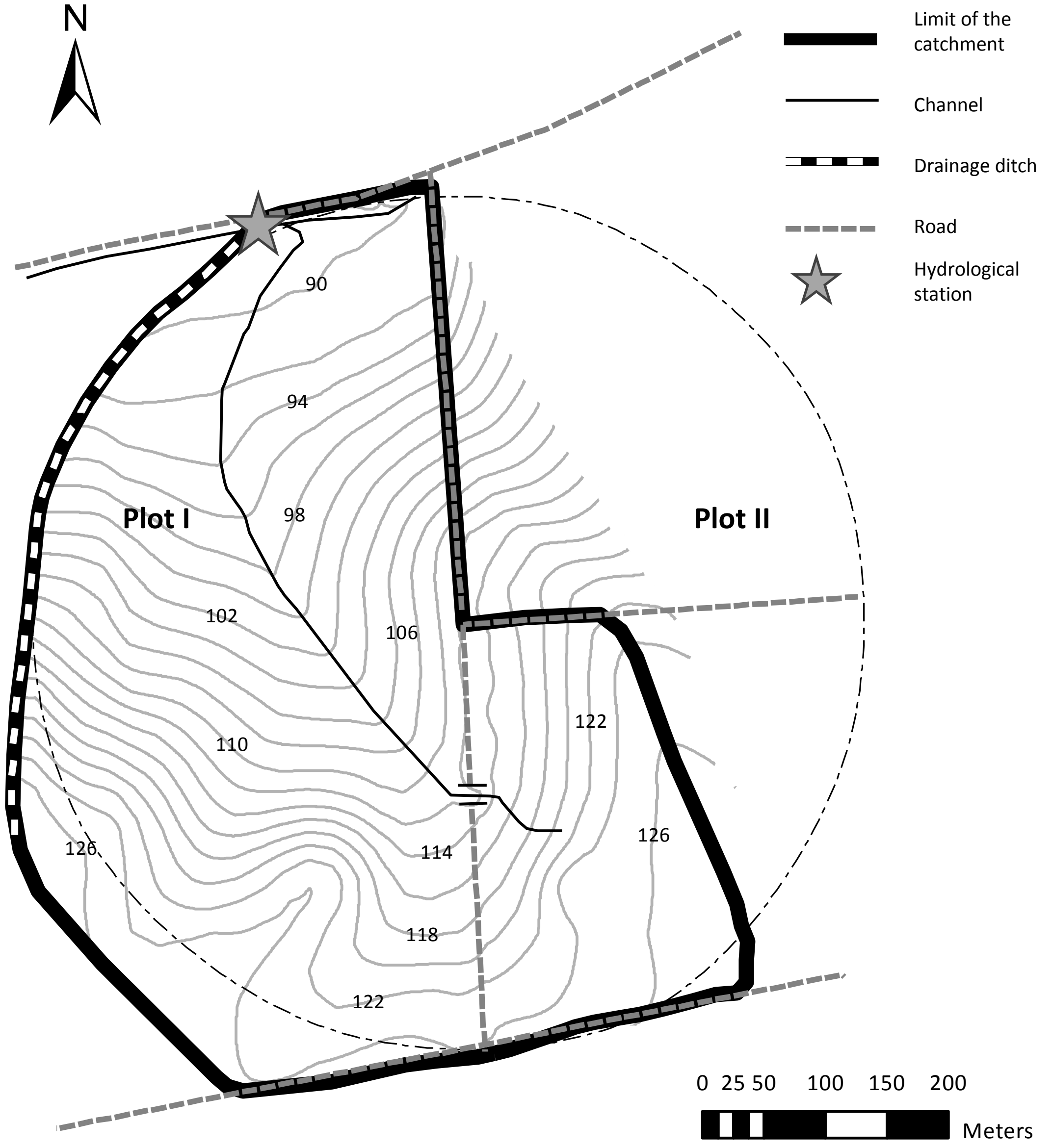

Figure 18. Study catchment, indicating, limits, plots, the location of the hydrological station, and other relevant geographic features.

The primary crop rotation in both plots is maize (*Zea mays* L.)-cotton (*Gossypium hirsutum* L.)-wheat (*Triticum aestivum* L.) (Table 11). Exceptions to this general sequence were cotton in 2007 followed by corn in 2008 (Plot I), and onion (*Allium cepa* L.) and sunflower (*Helianthus annuus* L.) grown in 2007-2008 on Plot II and Plot I, respectively (Table 11).

Summer crops, i.e., maize and cotton, are grown on raised-beds 0.95-m apart, with seeds being directly drilled onto the top of the beds. Maize stubble lying on the top of the beds is displaced to the furrows, before cotton sowing, using a rake. Wheat is broadcasted soon after soil is minimally tilled by passing a shallow harrow for burying wheat seeds while cotton stalks remain standing up. After wheat harvest in late June (leaving standing stems as high as possible to minimise their degradation), the soil is disked and beds that will support the following maize crop are formed again, facilitating also germination of remaining wheat seeds after the first autumn rainfalls. This wheat cover crop is chemically killed in midwinter and then furrows that support traffic (80% of the furrows) are decompacted using a paraplow subsoiler with legs angled 45° that work to 0.3 m depth.

Table 11. Crops grown in Plot I and Plot II, sowing and harvest dates, rainfall and irrigation depths, runoff coefficient (*QC*), deficit coefficient (*DC*), relative water supply (*RWS*), relative irrigation supply (*RIS*), irrigation efficiency (*IE*), and yields in the study catchment during the study period.

Plot	Crop	Sowing date	Harvest date	*R* mm	*I* mm	*QC*	*DC*	*RWS*	*RIS*	*IE*	Yield Mg ha^{-1}
I	Cotton	24-Apr-07	22-Oct-07	168	330	0.04	0.31	0.58	0.44	1.00	3.0
	Maize	14-Mar-08	14-Aug-08	317	379	0.07	0.10	0.93	0.58	1.00	11.5
	Sunflower	14-Mar-08	5-Aug-08	317	107	0.12	0.37	0.64	0.17	1.00	3.0
	Cotton	7-May-09	10-Oct-09	22	315	0.00	0.40	0.42	0.39	0.99	2.2
	Wheat	23-Nov-09	10-Jun-10	983	24	0.18	0.22	2.18	0.08	0.96	5.0
	Maize	25-Mar-11	3-Sep-11	258	493	0.02	0.14	0.82	0.59	1.00	12.5
	Cotton	2-May-12	15-Oct-12	144	561	0.03	0.15	0.75	0.70	1.00	2.1
II	Wheat	22-Nov-06	20-Jun-07	333	34	0.01	0.22	0.66	0.11	0.83	5.0
	Onion	1-Dec-07	4-Jul-08	426	138	0.09	0.09	1.17	0.45	0.93	40.0
	Maize	18-Mar-09	1-Sep-09	49	554	0.00	0.16	0.69	0.68	1.00	13.0
	Cotton	5-May-10	10-Oct-10	125	310	0.00	0.32	0.55	0.43	0.99	2.7
	Wheat	25-Nov-10	10-Jun-11	790	48	0.14	0.02	1.76	0.23	0.53	5.3
	Maize	20-Mar-12	5-Sep-12	110	672	0.02	0.05	0.84	0.81	0.99	14.5

Furrows and beds, and therefore plant rows, have north-south orientation, which coincides with the steepest slopes in most of the catchment (Figure 18).

The irrigation system is a centre pivot machine that was evaluated following Keller and Bliesner (1990) to determine its distribution uniformity, which was 90%. All farming activities (soil tillage, pesticide and fertilizer applications, planting and harvesting) were recorded. These records detailed the date, type of machinery used, product type and amount, and other ancillary information.

4.2.2. Hydrological station and runoff water sampling

The hydrological station (Figure 19) consists of a long-throated flume, an ultrasonic water level sensor (Siemens Milltronics, model *The Probe*), an automatic water sampler (Teledyne ISCO, model *ISCO 3700C*), an automatic tipping bucket rain gauge (*SH2O*, model *ECRN-100*), and a data logger and transmission system (Campbell Scientific, model *CR10X*). A complete automatic meteorological station was installed at 800 m away from the catchment and it has been collecting data since 17 May 2007. Before that date, daily meteorological data were provided by a weather station installed in the farm.

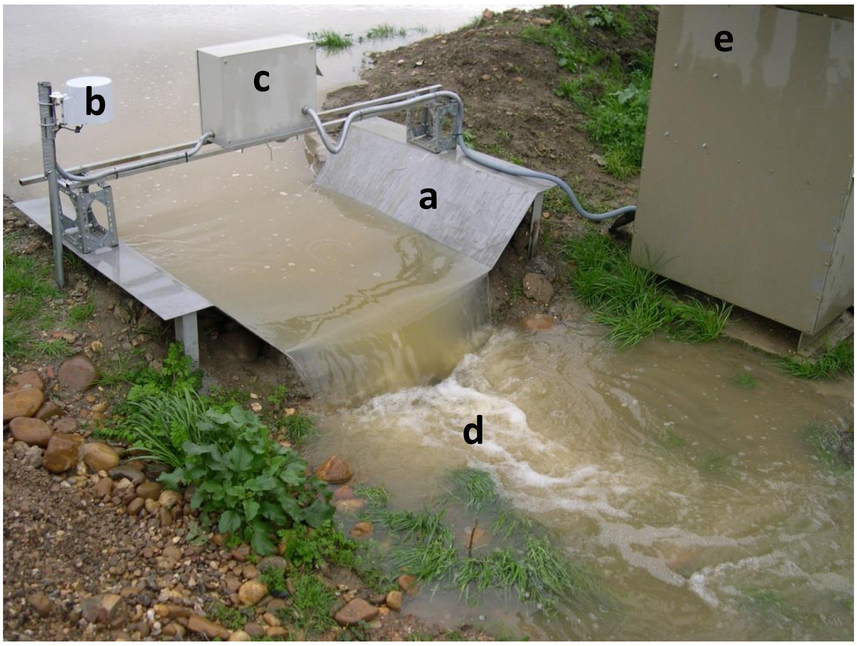

Figure 19. Hydrological station. (a) flume, (b) rain gauge, (c) ultrasonic water level sensor, (d) water sampling point, and (e) cabin containing the water sampler, data logger and ancillary equipment.

Runoff water has been measured since 28 September 2006. Rainfall at the hydrological station has been recorded since 13 February 2008. Water samples have been collected also since 13 February 2008, by using a sampling protocol that considers time interval and runoff volume between samples. Sediment mass present in the known volume of the water sample is determined after drying at 105 °C. Nitrate and herbicides concentration is determined in specific samples that are kept in amber glass bottles at 5 °C until analysis in the laboratory.

In this study we present rain, runoff, and sediment loss data measured until March 2013.

4.2.3. Water balance

Daily root zone water balances were computed for Plot I and Plot II. The water balance was formulated as:

$$RZWD_i = RZWD_{i-1} - R_i - I_i + ET + Q_i + D_i \qquad (2)$$

where $RZWD_i$ and $RZWD_{i-1}$ (mm) are the root zone soil water depletion on days i and i-1, respectively, and R_i, I_i, ET_i, Q_i and D_i (all in mm) are rainfall, irrigation, crop evapotranspiration, runoff, and drainage, respectively, on day i. It is assumed that the root zone is full of water, $RZWD = 0$, when its water content is at the drained upper limit, and that it is empty when the water content is at the lower limit of plant extractable water (Ritchie, 1981).

Rainfall was measured with the rain gauge described in the previous section. Evapotranspiration was estimated using the FAO methodology, based on the concepts of crop coefficient and reference evapotranspiration (Allen *et al.*, 1998), with meteorological variables measured at the nearby weather station. The crop coefficients were computed using the FAO dual approach (Allen *et al.*, 1998):

$$ET = (K_{cb}\, K_s + K_e)\, ET_o \qquad (3)$$

where K_{cb} is the basal crop coefficient, K_e is the soil evaporation coefficient, and K_s quantifies the reduction in crop transpiration due to soil water deficit.

A specific K_{cb} curve was drawn for each of the two fields based on initial, mid-season, and late-season crop-characteristic values (Table 12) taken from Allen *et al.* (1998), the recorded dates of planting and harvesting (Table 11), and periodic observations of crop ground cover. The stress coefficient, K_s, was assumed to be unity (no stress) when water content in the root zone was greater than a crop-dependent fraction ($1 - p$) of the root zone water holding capacity (Table 12) below which transpiration is assumed to decrease linearly to reach zero at the lower limit of plant extractable water (Allen *et al.*, 1998). The root zone depth was calculated as a function of estimated maximum and minimum depths (Table 12) and K_{cb} (Martin *et al.*, 1990).

Table 12. Basal crop coefficients, maximum root depths and depletion factors used for water balance computations.

Crop	Basal crop coefficients (K_{cb})			Maximum root depth	Depletion fraction for no stress
	Initial	Mid-season	Late season	m	(p)
Onion	0.15	0.95	0.65	0.7	0.50
Cotton	0.15	1.13	0.45	1.5	0.65
Wheat	0.15	1.10	0.15	1.3	0.55
Maize	0.15	1.15	0.15	1.5	0.55
Sunflower	0.15	1.10	0.25	1.5	0.45

Source: Allen *et al.* (1998).

Irrigation runoff was assumed negligible for the purpose of the water balance. Rainfall runoff (Q_i) was predicted from daily precipitation using an adaptation (Williams, 1991) of the USDA Soil Conservation Service curve number method (SCS, 1972; USDA/NRCS, 2004). The primary equation for calculating the runoff (Q) caused by a storm of precipitation P is:

$$Q = \frac{(P - 0.2\,S)^2}{(P - 0.2\,S) + S} \quad (4)$$

where S is:

$$S = 254\left(\frac{100}{CN}\right) - 1 \quad (5)$$

and CN is the curve number (the factor 254 is only to convert from inches, the units of S in the original equation, to mm, the units used in this paper). The adaptation of Williams (1991), first, corrects CN based on land slope, second, corrects S accounting for the soil water depletion computed through the soil water balance, and, third computes daily Q (Q_i)

entering P_i in equation (4). CN was calibrated to obtain a single value for the catchment by minimizing the root mean square deviation of measured and estimated (sum of the two fields) runoff for monthly periods. The obtained CN was 69.

Drainage (D) was estimated as the residual component in the catchment water balance as follows:

$$D_i = \Delta RZWD_i + R_i + I_i - ET_{act,i} - Q_i \qquad (6)$$

where $\Delta RZWD_i$ represents the differences between $RZWD$ on days i and i–1.

The daily water balance was run with three purposes: i) to have an estimation of $RZWD$ at the time of runoff events, ii) to estimate actual ET, and iii) to compute optimum irrigation schedules. For the last purpose, irrigation was triggered at a value of $RZWD_i$ equal to the management-allowed depletion, and the required irrigation depth (I_{req}) needed to return the root zone back to field capacity ($RZWD$ = 0) was calculated. Then, $ET_i = ET_{pot,i}$, with ET_{pot} defined as the ET in absence of water deficit. Actual evapotranspiration of each plot ($ET_i = ET_{act,i}$) was calculated with the model entering recorded irrigation dates and depths.

The water balance was computed for each crop in the period comprised from December 2006 to October 2012.

4.2.4. Water use indicators

The following performance indicators were used to assess the hydrological behaviour of the catchment and the strategy followed by the farmer supplying water to the crops:

Runoff coefficient: $QC = \frac{Q}{R+I}$ (7)

Relative water supply: $RWS = \frac{R+I}{ET_{pot}}$ (8)

Relative irrigation supply: $RIS = \frac{I}{I_{req}}$ (9)

Deficit coefficient: $DC = 1 - \frac{ET_{act}}{ET_{pot}}$ (10)

Irrigation efficiency: $IE = \frac{ET_I}{I-\Delta A}$ (11)

RWS and RIS (Molden and Gates, 1990) are two performance indicators increasingly used in the irrigation literature because they provide a succinct indication of whether there is an insufficient amount of water to meet crop water demands or whether the amount of irrigation or total water supplied is excessive. *IE* is defined as the ratio between the irrigation water used beneficially, which we define here as the irrigation water that is evapotranspirated (ET_I), and the irrigation water applied (I) minus the increment of storage of irrigation water (ΔA) during the period of interest (Burt *et al.*, 1997). ET_I was calculated as the difference between ET_{act} and rainfall during the period of interest ($ET_I = ET_{act} - R$).

4.3. Results

The period under study was quite variable in terms of rainfall (Table 13). The hydrological years 2009-2010, 2010-2011 and 2012-2013 were wet, while the rest had rainfall close to the average (2006-2007, 2007-2008) or below the average (2008-2009, 2011-2012). The winter of 2009-2010 and the fall of 2010-2011 were particularly rainy. Annual runoff was closely related to annual rainfall (Table 13). The periods of highest runoff were December 2009 to February 2010 and December 2010. *QC* for the period October 2009-March 2010 reached 0.25. Most of the little runoff that occurred during the summer was due to irrigation. Annual *QC* was 0.14.

151 runoff events were recorded from September 2006 to March 2013. Individual events were separated when more than six hours mediated between zero runoff and initiation of runoff. Among the 150 events, 90 were caused by rainfall and accumulated 611 mm of runoff. The other 61 events were caused by irrigation, totalling 6 mm. Irrigations in Plot I caused most of the irrigation-induced runoff, mainly while irrigating maize. Only nine of the 61 irrigation runoff events were caused during irrigation of Plot II, which contributed with 3% of the irrigation runoff.

The largest annual sediment loss (4383 kg ha^{-1}) did not occur on a particularly rainy year or period of great runoff but in 2007-2008. Rainfall that year (571 mm) was close to the mean rainfall, although it was concentrated in April (Table 13), mainly in two events that will be discussed below. Significant sediment losses were recorded also during December 2009 to February 2010 and in December 2010, coinciding with highest monthly runoff. The mean annual sediment loss for the four complete hydrological years of analysis was 2.4 Mg ha^{-1} y^{-1}. Only 0.05 Mg ha^{-1} y^{-1} of this loss (2%) was caused by runoff events generated by irrigation. The maize crops grown in 2008 and 2011 were responsible for most of the irrigation-induced sediment loss.

Table 13. Monthly rainfall (R), irrigation depth in Plots I and II (I_{PlotI} and I_{PlotII}), runoff (Q) and soil loss (SL) caused by rainfall and irrigation.

	2006 - 2007							2007 - 2008							2008 - 2009							2009 - 2010						
	Rainfall			Irrigation				Rainfall			Irrigation				Rainfall			Irrigation				Rainfall			Irrigation			
	R	Q	SL	$I_{Plot\,I}$	$I_{Plot\,II}$	Q	SL	R	Q	SL	$I_{Plot\,I}$	$I_{Plot\,II}$	Q	SL	R	Q	SL	$I_{Plot\,I}$	$I_{Plot\,II}$	Q	SL	R	Q	SL	$I_{Plot\,I}$	$I_{Plot\,II}$	Q	SL
	mm	mm	kg ha^{-1}	mm	mm	mm	kg ha^{-1}	mm	mm	kg ha^{-1}	mm	mm	mm	kg ha^{-1}	mm	mm	kg ha^{-1}	mm	mm	mm	kg ha^{-1}	mm	mm	kg ha^{-1}	mm	mm	mm	kg ha^{-1}
Oct	90	7	-					20	0	-					70	0	11					47	0	80				
Nov	99	21	-					77	2	-		14	0	0	36	0	-					35	0	0	24		0	0
Dec	39	9	-					0	0	-		15	0	0	55	0	1					359	103	1222				
Jan	32	0	-					67	6	-					70	1	14					141	18	523				
Feb	66	6	-					46	1	19		10	0	0	112	31	230					277	99	1052				
Mar	17	0	-		21	0	0	2	0	0	23	30	0	0	87	6	44		17	0		98	24	110				
Apr	50	2	-		13	0	0	211	63	4218	3	12	0	0	17	0			16	0		72	0	1				
May	103	17	-	26		0.2	-	99	0.4	11		33	0	0	1	0		52	119	0.038	-	11	0					
Jun	0	0	-	59		0.3	-	1	0	26	116	25	0.4	33	2	0		40	160	0.001	-	37	0			28	0	0
Jul	0	0	-	122		0	0	3	0	0	100		1.8	72	0	0		101	202	0.014	-	0	0			133	0	0
Aug	2	0	-	123		0	0	1	0.1	4					1	0		121	39	0.005	-	14	0			133	0	0
Sep	33	12	-					45	0	-					9	0						11	0			16	0	0
Total	532	74	-	330	34	0.5	-	571	73	4279	243	138	2	105	460	38	300	315	554	0.06	-	##	243	2989	24	310	0	0

Dashes before February 2008 mean that soil losses could not be estimated becasue the water sampler had not been installed in the hydrological station yet. Dashes from September 2009 mean that soil losses were not measured becasue none of the events in that month reached the minimum depth required to collect a sample. Irrigation depth in Plot I in 2007 - 2008 is the average between irrigation depth of maize and sunflower.

Table 13. (continued)

	2010 - 2011							2011 - 2012							2012 - 2013						
	Rainfall			Irrigation				Rainfall			Irrigation				Rainfall			Irrigation			
	R	Q	SL	$I_{Plot\ I}$	$I_{Plot\ II}$	Q	SL	R	Q	SL	$I_{Plot\ I}$	$I_{Plot\ II}$	Q	SL	R	Q	SL	$I_{Plot\ I}$	$I_{Plot\ II}$	Q	SL
	mm	mm	kg ha^{-1}	mm	mm	mm	kg ha^{-1}	mm	mm	kg ha^{-1}	mm	mm	mm	kg ha^{-1}	mm	mm	kg ha^{-1}	mm	mm	mm	kg ha^{-1}
Oct	121	0	4					43	0	0					108	3	23				
Nov	100	1	9					106	3	45					198	50	337				
Dec	350	69	453					15	0	0					38	1	6				
Jan	49	4	390					15	0	0					51	2	20				
Feb	69	6	49					1	0	0					104	17	119				
Mar	57	1	9					8	0	0		36	0	0	230	59	422				
Apr	134	14	151	20	48	0	0	37	0	0		26	0	0	78	16	68				
May	62	5	138	72		0	0	68	4	100	36	101	0	0	17	0	0				
Jun	20	2	73	198		2	85	0	0	0	101	229	0.1	3	2	0	0				
Jul	2	0	0	191		1	14	1	0	0	188	218	0.1	3							
Aug	0	0	0	11		0	3	3	0	0	204	61	0	0							
Sep	34	0	0					71	0	0	31		0	0							
Total	999	104	1274	493	48	4	103	368	8	145	561	672	0.2	6	826	147	995	0	0	0	0

4.3.1. Precipitation-runoff event description

Figure 20 shows examples of hyetographs and runoff hydrographs. Figures from 20a to 20e correspond to rainfall events whereas Figure 20f corresponds to an irrigation event. In all the examples, soil water content preceding the events was high or relatively high. The soil was fallow (Figures 20a,b,d) or cropped (Figures 20c,e,f). The shape of the runoff hydrographs was related to the shape of the respective hyetographs. The hydrographs increased shortly after the start of the rainfall events and reached a peak after maximum rainfall intensity occurred. The catchment lag time (the difference between the peak of the rain event and the peak discharge) was about 100 minutes. The example of irrigation event (Figure 20f) shows the field-averaged application rate and the runoff hydrograph. The scale in this figure is different to the scale in the companion figures: runoff rate was much less than that for the rainfall event examples, and field-averaged irrigation application rate was also less than the rainfall intensity of the examples. The pattern of the irrigation runoff hydrograph, characterized in this example by three peaks, necessarily must be related to the positions/movement of the irrigation machine.

The trend of the suspended sediments concentration (SSC) roughly followed that of the hydrographs, although generally it lagged beyond and behind during the rising and recession limbs, respectively. This phenomenon (hysteresis) is observed more clearly in Figs. 21, where the SSC-runoff rate data points of Fig 20a are linked in time sequence.

4.3.2. Effect of preceding moisture, rainfall intensity, and ground cover on the runoff-rainfall relationship

The precipitation-runoff events recorded after installation of the rain gauge at the hydrological station (74 events) are presented in Figure 22 using different symbols according to preceding soil moisture (estimated with the water balance) and maximum rainfall intensity in 30 minutes intervals ($RInt$). The solid line represents the SCS curve for CN = 65, the value that best fitted all measured data. As expected, events of high rainfall intensity that occurred on wet soil (filled squares in Figure 22) were on the upper bound of the points cloud, or at least above the curve adjusted to the whole data set. Contrary, events of low rainfall intensity on dry or relatively dry soil (open circles) should be below the adjusted curve. This is also appreciated in Figure 22, although less clear because this kind of events had rainfall of less than 40 mm. Note that the data points corresponding to soil water deficit less than 5 mm were near the upper bound, whereas those corresponding to dry soil where in general near the lower bound, irrespectively of *RInt* being higher or lower than 20 mm h^{-1}.

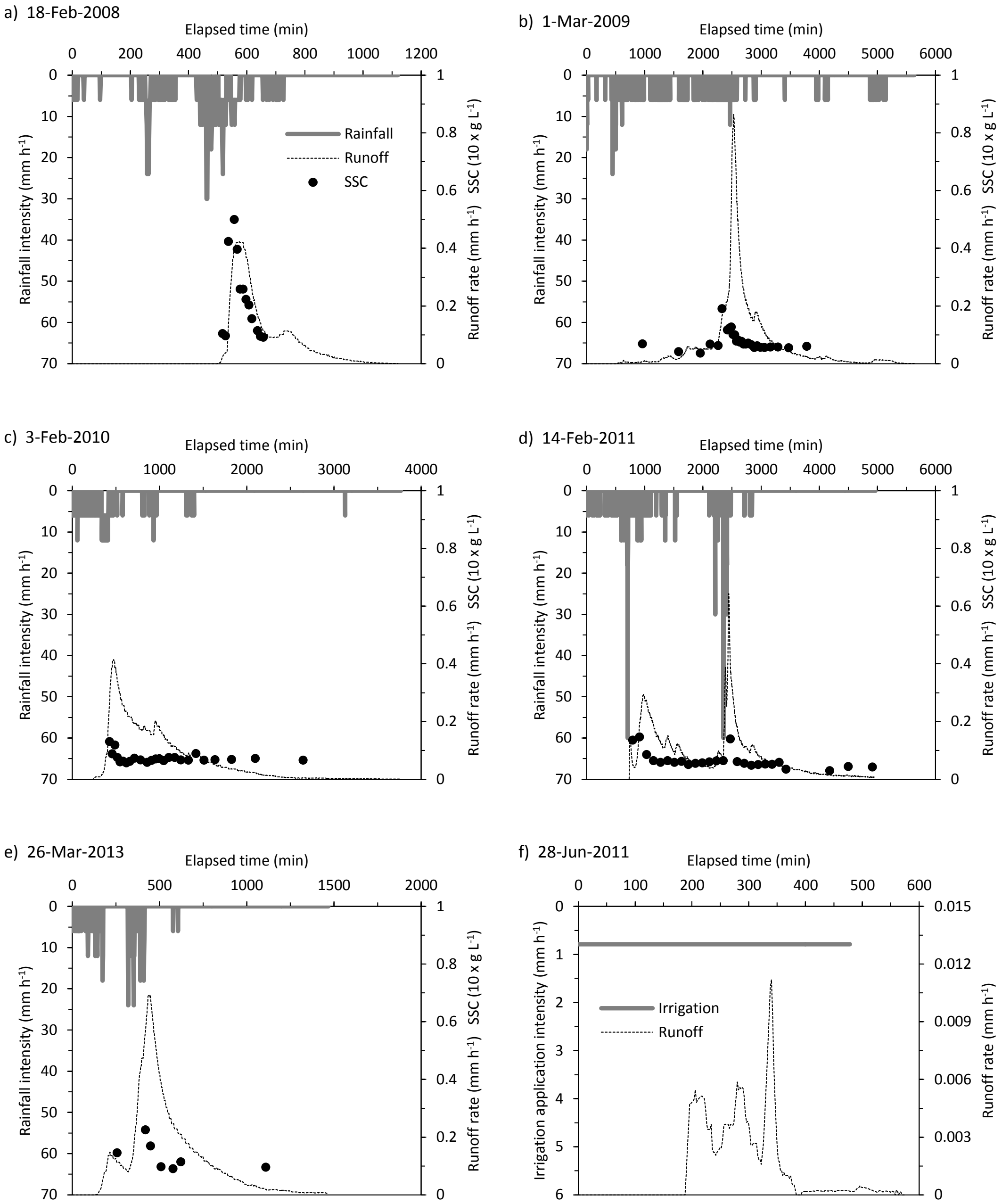

Figure 20. Rainfall, runoff and suspended sediment concentration (SSC) for six runoff events under different catchment conditions in terms of land use and soil coverage: (a) Rainfall event of 18 Feb 2008: fallow after cotton, root zone water deficit (RZWD) 24 mm, rainfall depth 31 mm, rainfall intensity for 30 min 10.8 mm h^{-1}; (b) Rainfall event of 1 Mar 2009: fallow after maize/sunflower, RZWD 21 mm, rainfall depth 46 mm, rainfall intensity for 30 min 6 mm h^{-1}; (c) Rainfall event of 3 Feb 2010: wheat crop, RZWD 11 mm, rainfall depth 34 mm, rainfall intensity for 30 min 10.8 mm h^{-1}; (d) Rainfall event of 14 Feb 2011: fallow after wheat, RZWD 14 mm, rainfall depth 48 mm, rainfall intensity for 30 min 14.4 mm h^{-1}; (e) Rainfall event of 26 Mar 2013: wheat crop, RZWD 5 mm, rainfall depth 24 mm, rainfall intensity for 30 min 6.4 mm h^{-1}; (f) Irrigation event of 28 Jun 2008: 6.3 mm of irrigation applied during 8 hs.

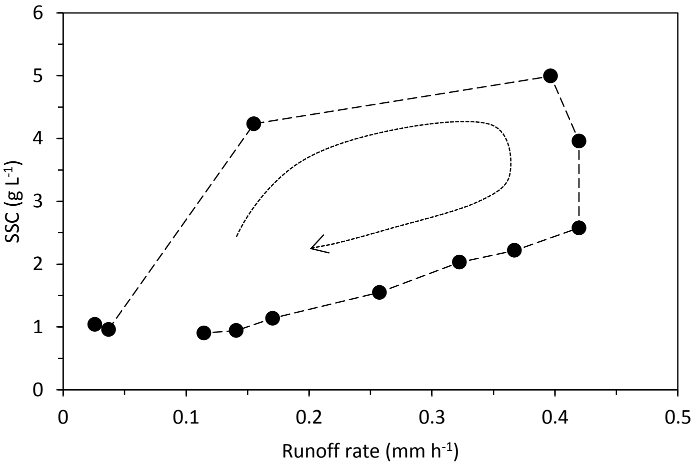

Figure 21. Runoff rate and suspended sediment concentration (SSC) relationship showing *clockwise-type* hysteresis in a rainfall-runoff event on 18 February 2008.

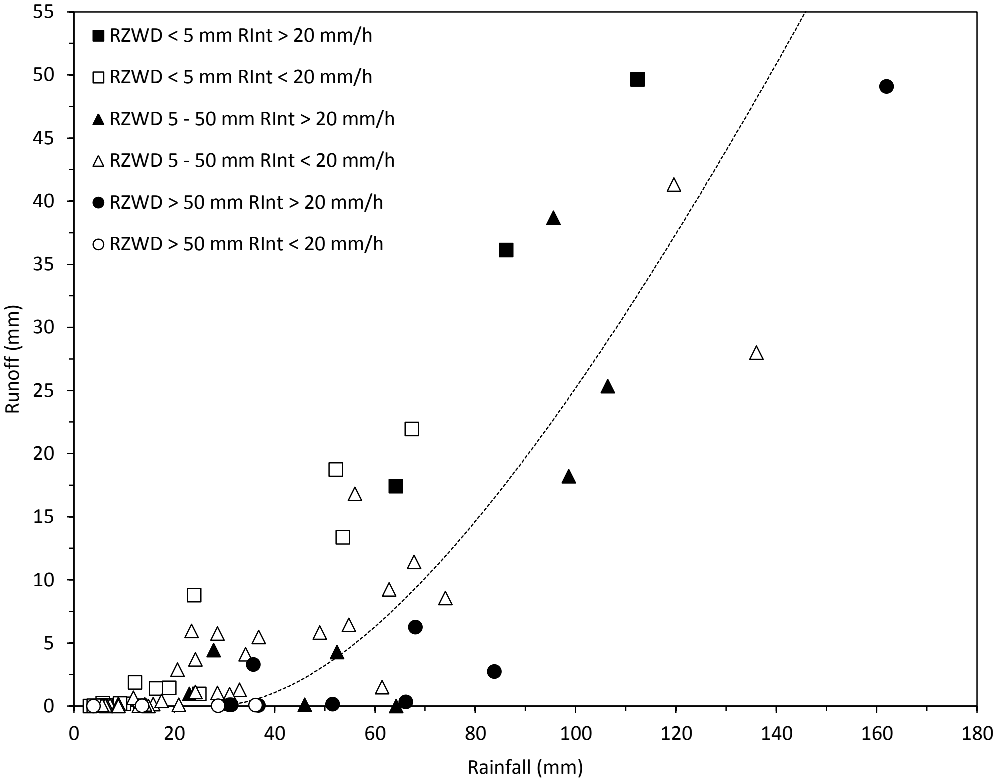

Figure 22. Rainfall-runoff relationship for events with varying soil water deficit (*RZWD*) in Plot I and maximum rainfall intensity determined for periods of 30 minutes.

Data shown in Figure 22 are also presented in Figure 23 but using symbols that differentiate ground cover at the time of the rainfall event in Plot I, the largest one of the two plots (crop and preceding crop, the latter as an indication of the type and amount of residues on the soil surface). Below the SCS curve corresponding to *CN* = 65 there are data points for events over fallow after wheat (open circles) or cotton (open triangles). The events corresponding to wheat after cotton (filled circles), fallow after maize (open squares) and maize after cotton (grey triangles) are above the curve.

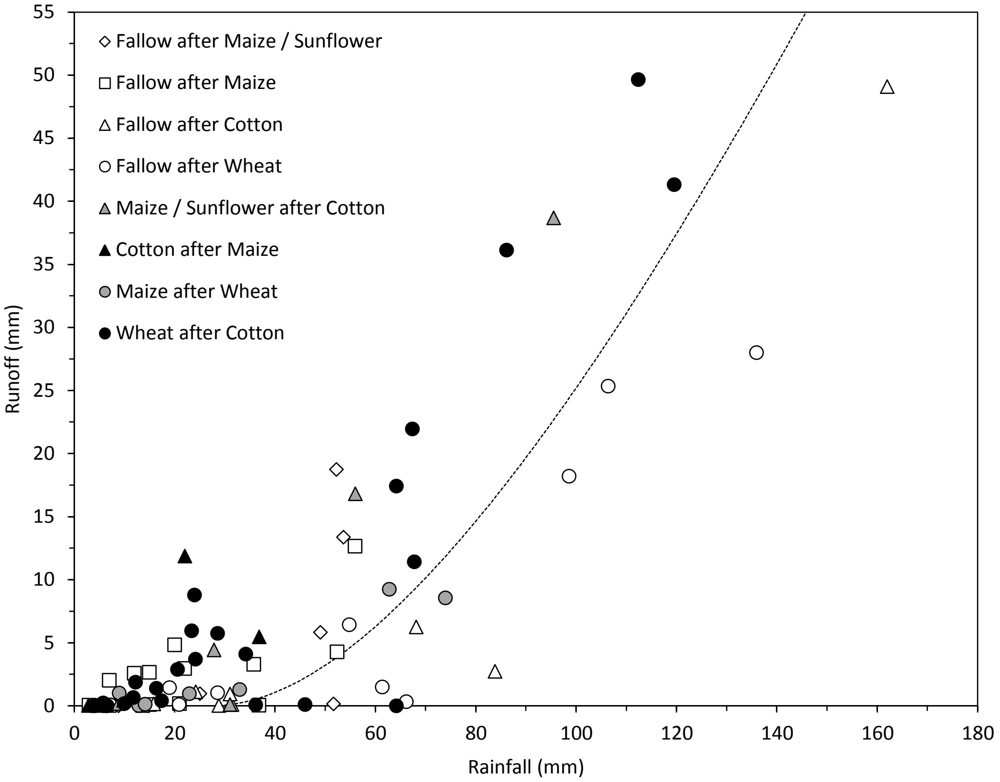

Figure 23. Rainfall-runoff relationship for events over soil with different crop and residues ground cover (the later indicated by the previous crop) in Plot I.

4.3.3. Runoff-sediment loss relationships

The same 74 events were used to analyse runoff-sediment loss relationships. Overall, sediment loss increased with runoff (Figure 24) except for four events. A straight line could be fitted to the events for which the sediment loss was less than 375 kg ha^{-1} (Figure 24).

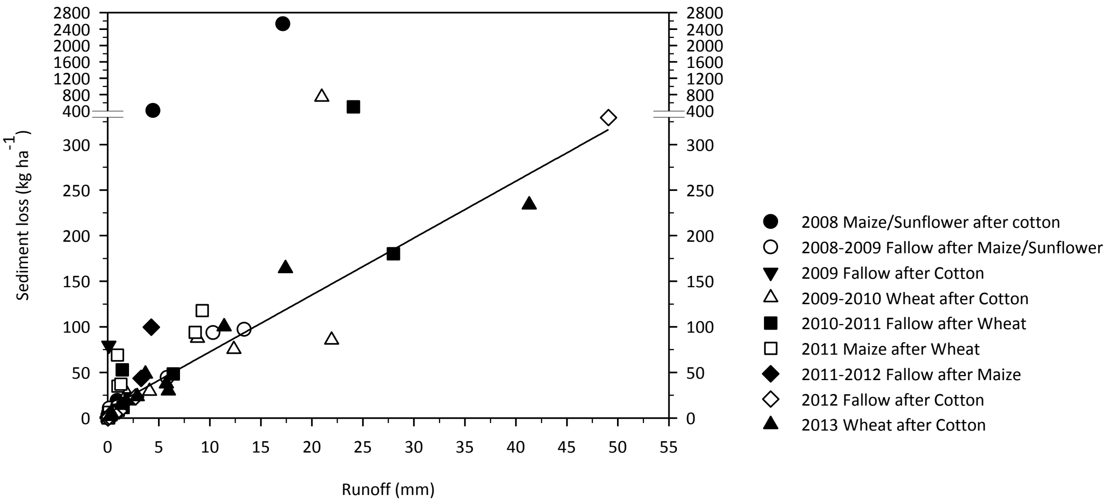

Figure 24. Sediment losses vs. runoff depth for recorded rainfall runoff events. The events are grouped by cropping season and crop in Plot I.

Two of the four events with extreme sediment losses occurred in April 2008 over the maize and sunflower crops planted after cotton in the main plot. Both ground covered by cotton residues and ground covered by the canopy of any of the two crops were very small at the time of those events (Figure 25a). Moreover, soil was rather full of water when the events started (*RZWD* less than 24 mm), rainfall depths were high (27 and 96 mm), and precipitation rate was intense (*RInt* equal to 26 and 29 mm h^{-1}, respectively). Under these conditions, runoff and soil erosion were expected to be considerable, but it was striking that these events produced sediment losses one order of magnitude greater than the losses expected according to the linear relationship that fitted the bulk of events. We were able to analyse closer some of the factors that controlled these extreme events by comparing them with two events that occurred in April 2011 (runoff 9.2 and 8.6 mm and sediment loss 118 and 94 kg ha^{-1}, respectively), when the crop in the main plot was also maize, but planted just after killing with herbicides the spontaneous wheat that grew vigorously after germination of falling seeds from the previous year (Figure 25b). Figure 26a presents SSC vs. rainfall runoff rate. Even though runoff rates were lower in 2008 than in 2011, SSC was in most cases higher; becoming the difference evident at runoff rates greater than 1 mm h^{-1}. This was even more evident with the irrigation runoff events recorded the same two years (Figure 26b). Despite irrigation generating more runoff in 2011 than in 2008, SSC was in 2011 remarkably lower than in 2008.

4.3.4. Seasonal water balance and crop water use indicators

Crop water use is summarized in Table 13. Overall, the crops suffered some degree of water deficit, which was more intense in the cotton and sunflower crops. Maize and onion were the two crops for which the strategy was closer to full irrigation. The *RIS* of wheat was very low, but irrigation is only supplemental for this crop because rainfall covers most of its evapotranspiration demand. That is why *RWS* of wheat was high and the *DC* was moderate or low.

IE was high or very high, mainly due to the deficit irrigation strategy but also because irrigation water was applied timely with high frequency and low depths. The relatively low *IE* of the wheat crops was surely due to errors in the estimation of ET_I and ΔA (equation 11), since ET_{act} and R (the two addends to compute ET_I, the numerator of equation 11), and I and ΔA (the two terms in the denominator of the equation) were of similar magnitude. Thus, small errors in the water balance used to compute ET_{act} and ΔA could lead to large errors in *IE*.

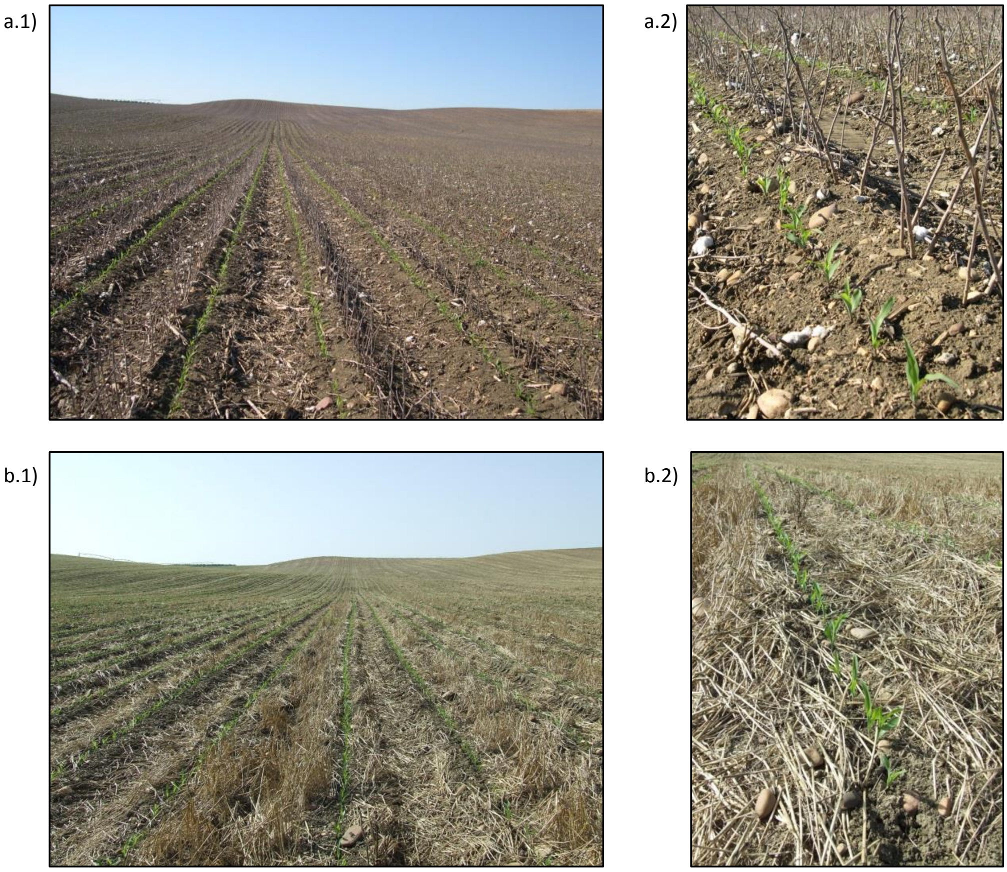

Figure 25. General and detail views of Plot I on 4 April 2008 (a.1 and a.2) and on 8 April 2011 (b.1 and b.2). Short maize plants are already visible.

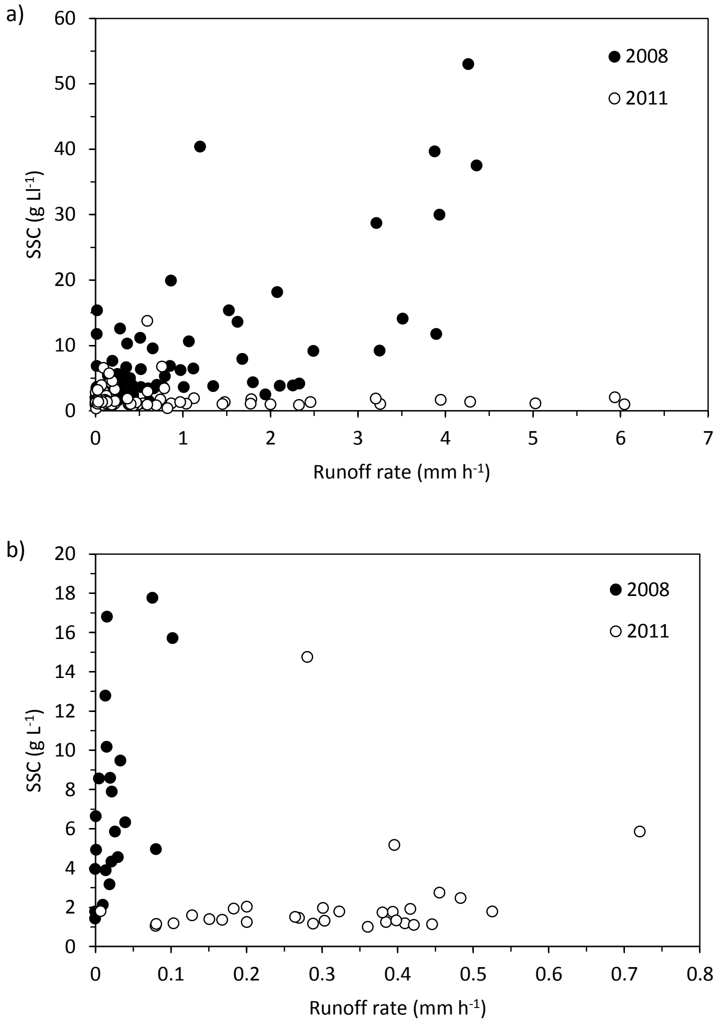

Figure 26. Runoff rate and corresponding suspended sediment concentration (SSC) for samples taken during runoff events caused by rainfall (a) and irrigation (b) during the 2008 and 2011 cropping seasons.

4.4. Discussion

4.4.1. Runoff coefficient and sediment losses

Rainfall and runoff were higher in winter than in summer, whereas irrigation predominated during the summer to cover water demand for spring crops. The average monthly *QC* increased roughly during fall and winter, peaking in February (0.22), and decreasing during spring (Figure 27). Mean annual *QC* was 0.14, and mean annual soil loss 2.4 Mg ha^{-1} y^{-1}. Despite the fact that soil loss tolerance is a controversial concept (Johnson, 1987; Li *et al.*, 1987), it helps to establish references. Soil loss tolerance at the catchment, estimated using the methods of Stamey and Smith (1964) and USDA/NRCS (1999), varied between 10 and 14 Mg ha^{-1} y^{-1}, depending on the assumptions and the method used. Therefore, 2.4 Mg ha^{-1} y^{-1} can be categorized as a tolerable soil loss. However, this value is greater than the 1.8 Mg ha^{-1} y^{-1} measured by Taguas *et al.* (2013) in a nearby 6.1-ha catchment grown with olives, a crop that has been argued to cause severe erosion in Andalusia (Gómez and Giráldez, 2009; Gómez-Limón *et al.*, 2012). Three of the years of the study by Taguas *et al.* (2013) coincided with our study period. The relatively low precipitation recorded by these authors (and the consequent annual QC = 5.6) may explain this unexpected result. Moreover, in year 2009-2010 Taguas *et al.* (2013) measured 621 mm of rainfall, QC of 0.12, and soil loss of 5.9 Mg ha^{-1} y^{-1}, while 1103 mm, 0.21, and 3.4 Mg ha^{-1} y^{-1}, respectively, were recorded in this study (Table 13). These values contrast with those that we expected: a catchment of 27.42 ha farmed with annual crops using soil conservation practices should generate less runoff and soil loss per unit of area than a 6.1-ha catchment grown with an olive orchard where the only soil conservation practice was allowing the growth of spontaneous weeds.

Another relevant study on the hydrology of catchments cultivated with annual crops has been carried out in Navarra, northern Spain. Casalí *et al.* (2008) reported rainfall, runoff, and soil loss data for nine years in two catchments (of 169 and 207 ha each). Mean annual precipitation was 770 and 691 mm, the runoff coefficient was 0.30 and 0.23, and soil loss 1.98 and 0.29 Mg ha^{-1} y^{-1}. However, one of the catchments included subcatchment studies for areas similar to that of our study catchment, and the sediment loss per unit of area estimated by the mentioned authors was then one order of magnitude greater than what they obtained for the entire catchment.

The above QC and soil losses and the limited comparison possible with other catchments do not allow drawing clear conclusions about which hydrological conditions (topography, soil, land use, crop management) contribute better to soil conservation. Hopefully, longer data series will provide average values with a level of confidence that we do not have today. Meanwhile, we can try to discern among factors that influenced QC and soil loss through an analysis of internal hydrological processes and crop management.

4.4.2. Interpretation of hydrological responses

Whenever the precipitation rate exceeds the infiltration capacity, water accumulates over the soil surface. Runoff begins when the surface storage is filled. In a permanent-bed cropping system combined with controlled-traffic, infiltration capacity varies with time but also spatially, from bed to furrow and from trafficked to non-trafficked furrow. Compaction and the amount of residues over the soil surface are the main factors controlling the variation of infiltration capacity (Boulal *et al.*, 2011), surface storage, and surface roughness among furrows. With the furrow-bed configuration in the study catchment, runoff is channelled along the furrows, discharging eventually into two natural channels that converge just upstream of the gauging station (Figure 18).

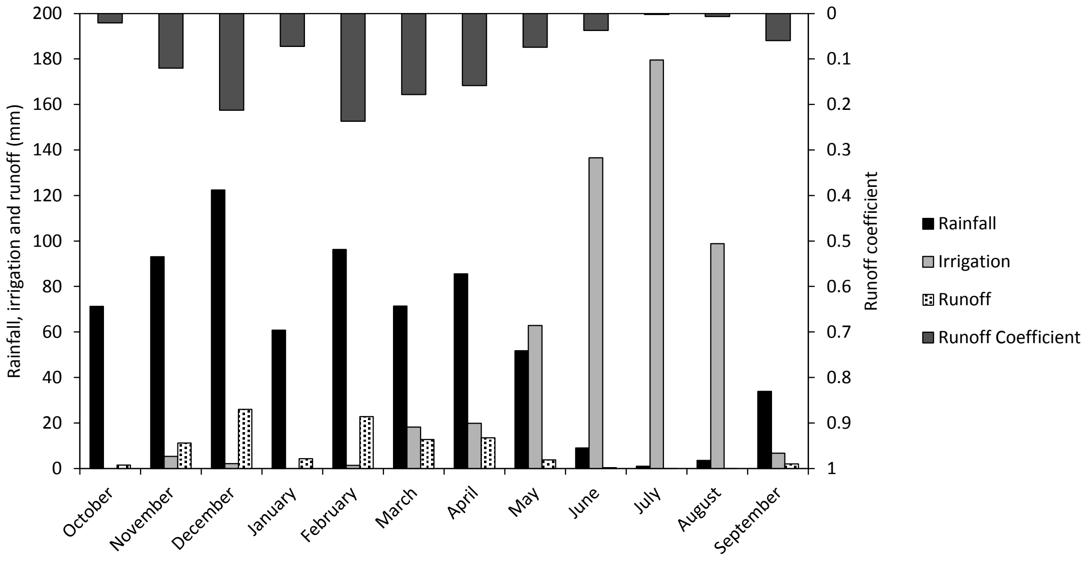

Figure 27. Monthly rainfall, irrigation, runoff, and runoff coefficient in the catchment averaged for the study period.

In most catchments, the rising limb of the hydrographs is steeper than the recession limb, indicating that during the initial stage of a storm, both overland flow (quick flow) and subsurface flow (interflow) feed water into the stream, and discharge increases rapidly; while during the recession stage, subsurface flow predominates (Te Chow *et al.*, 1988). This type of hydrograph shape was apparent in Figs. 20a,c,e, but not in Figure 20b or in the second pulse in Figure 20d. However, a simultaneous look at the hyetograph and hydrograph of each event unveiled that, when rainfall stopped just after peak flow (for instance, in the second pulse in Figure 20d), the recession limb decreased at similar rate than the rising limb increased. This pattern indicates that subsurface flow was irrelevant. Moreover, there was no base flow since discharge reduced to zero about 15 hours after rainfall ceased.

Although the application rate of centre pivot machines is constant with time, it varies spatially. For a given point in the area covered by the machine, application intensity increases as the lateral approaches that point, and it decreases as departs from it. This intensity also increases towards the outer part of the wetted circle, where it can be rather high. The oscillations in the runoff hydrograph observed in the catchment (Figure 20f) are likely related to the position of the centre pivot lateral. When it points towards south, the lateral is aligned with the furrows, thus runoff is expected in that position. As it moves clockwise, the lateral becomes perpendicular to the furrows direction, then runoff is less likely to occur; however, since the outer sectors in that position (those receiving highest application intensity) have the greatest slope (Figure 18), a second discharge peak could occur. When the lateral points to the north, it is aligned with the furrows while maximum application intensity occurs near the hydrological station. Runoff could be expected in that position as well. Unfortunately, we did not record the exact time of the lateral position, thus this interpretation of the three spikes in the runoff hydrograph of Figure 20f will need to be verified with new complete data sets.

In general, the hysteresis of the runoff rate-SSC relationship was clockwise type (for a given runoff rate, SSC is greater during the rising limb of the hydrograph than during the recession limb). A set of 17 events for which the hydrograph showed a clear bell shape with a minimum of five evenly distributed water samples was identified. Of the 17 events, 12 presented clockwise hysteresis (Williams, 1989), as in Figure 21, whereas the other five presented an "eight-shaped loop" –also observed by other authors (Gellis, 2013)– or did not present clear hysteresis. One of the 12 events that presented clockwise hysteresis was caused by irrigation. Some authors have related the occurrence of clock- or counter clock-wise hysteresis to the soil water content at the initiation of the event (Seeger *et al.*, 2004) or to the distance of the main source of sediments to the gauging station (Soler *et al.*, 2008). The clockwise pattern observed in our study catchment could therefore be interpreted as follows: sediments previously deposited near the outlet of the catchment are initially dragged producing large SSC; at the time of the falling runoff limb, this sediment source has exhausted, so SSC is less compared with SSC obtained for similar runoff rate during the rising limb (Steegen *et al.*, 2000; Gellis, 2013). Another interpretation for some of the clockwise patterns could be that during long periods with absence of runoff, soil aggregates break apart and form layers of fine particles or small aggregates laying on more structured soil. When the rain season begins ("flushing" period), these sediments are easily removed by runoff producing high initial SSC (Bartley *et al.*, 2006). The first flush in the study catchment typically occurs in October (average SSC in October was about five times SSC in June, the next month of highest average SSC), thus this interpretation of the clockwise hysteresis phenomenon could be valid to explain the high initial SSC observed in the events of October 2008 and October 2009. The “eight-shaped” pattern could be due to exhaustion of certain sources of sediments and ulterior contribution of other zones that could have served as temporal reservoirs for sediments (Eder *et al.*, 2010), i.e., zones of different slope and undulation comprised in the study catchment (Boulal and Gómez-Macpherson, 2010). This type of hysteretic behaviour is poorly described in the literature (Seeger *et al.*, 2004).

We acknowledge that these interpretations of the hysteresis phenomenon are rather speculative. At the same time, other simpler explanations, such as differences of transport capacity of the accelerating and decelerating flow during the rising and recession hydrograph limbs, respectively, could be plausible as well. Additional field data, laboratory experiments, and a physical analysis of the hydrodynamics of the process should give more insight into this hysteresis phenomenon.

Apparently, the factor “preceding moisture” was more determinant in the generation of runoff for a given rainfall depth than the factor “maximum precipitation intensity” (Figure 22). The experimental approach did not allow discriminating these two effects from “ground cover” effects. However, compared to other ground covers, “fallow after wheat” appeared to favour infiltration whereas precipitation over “wheat after cotton” generated more runoff, irrespectively of soil moisture. Apparently, subsoiling after the 2007 cotton crop in 2007 also reduced runoff. Multivariate statistical techniques may help to discriminate between effects (Giménez *et al.*, 2012), although we will need to add more events in the coming years to perform this analysis properly.

Soil conservation techniques have demonstrated to be comparatively more effective in terms of soil erosion reduction than in terms of runoff reduction (Maetens *et al.*, 2012). Other authors have shown the effect of land use and management on the SSC-runoff rate relationship (van Dijk and Kwaad, 1996; Steegen *et al.*, 2000). In our study catchment, the presence of residues covering the soil surface had a tremendous effect on protecting the soil from water erosion, likely from both rain splash and sheet/rill erosion. This was evident when comparing the events of April 2008 with April 2011 and the concentration of sediments in the irrigation runoff of the respective cropping seasons (Figure 26). The main difference between the catchment conditions in both cropping seasons was the amount of residues on the soil surface (Figure 25). The maize crop grown on Plot I in 2011 benefited from a rich mulch thanks to the preceding (wheat) cover crop. This confirmed the findings of Boulal et al. (2011a) at micro-plot scale, who demonstrated that permanent beds with crop residues retention had better performance in terms of soil erosion mitigation than conventional beds by reducing SSC to a much greater extent (by 83%) than by reducing runoff (by 18%). Crop management therefore allowed controlling total sediment loading through SSC, counteracting total runoff as usual governing factor (Puustinen *et al.*, 2007).

The role played by crop rotation on residues ground coverage was essential to understand the behaviour of the catchment along the years of observation. Situations like that occurring in the 2008 cropping season did not occur again because of the rotation established by the farmer thereafter. In 2008, the relatively low quantity of residues left by cotton crops and the long period from cotton harvest to planting the following maize/sunflower hindered sufficient protection of the soil surface. However, by shifting to the crop sequence maize-cotton-wheat, the soil would be protected with sufficient amount of residues during the autumn and winter periods.

4.4.3. Role of irrigation in conservation agriculture

Irrigation generated much less runoff and soil loss than rainfall despite contributing with about 40% of the water supply. There is an obvious reason for this difference: irrigation can be controlled whereas rainfall cannot. The performance indicators in Table 11 reflect efficient irrigation management, well adjusted to the pre-established strategy of full irrigation for maize and onion, deficit irrigation for cotton, and supplementary irrigation for wheat. Maize yield was between 11.5 and 14.5 Mg ha^{-1}. The later yield corresponded to Plot II in year 2012; the former, to Plot I in year 2008, when a short cycle hybrid was grown. Cotton yield in 2009 was close to the target yield, 2.5 Mg ha^{-1} (about half the potential yield), that is obtained using low nitrogen and irrigation inputs. The target yield was determined by cotton prices and subsidies applying to the farm each year. Because the target in 2012 was higher (3.5 Mg ha^{-1}), the farmer applied more irrigation water and more nitrogen than in 2009. In spite of this, actual yield was similar to that of 2009. The farmer attributed this low unexpected yield to the poor quality of the cotton seed.

Irrigation in this farm can be therefore considered as a reference for the region. Moreover, if conservation agriculture is practiced, irrigated crop production will leave more residues on the soil surface than rainfed production, and will also offer more opportunities to grow catch/cover crops such as the spontaneous wheat that grew in Plot I from September 2010 to March 2011. One may then conclude that, from the soil conservation point of view, irrigated agriculture offers more advantages than rainfed agriculture. However, irrigated agriculture uses more fertilizer inputs than rainfed agriculture. If not applied timely or if applied before heavy rain falls, a significant part of these fertilizers can be leached or carried off with the runoff water. Monitoring this effect should be part of the environmental impact assessment that can be carried out using hydrological stations such as the one used in this study. Figure 28 shows an example of observations of nitrate runoff after two applications of nitrogen fertilizer to the wheat crop grown in 2013 in Plot I. The nitrate concentration of 297 mg L^{-1} in the runoff water of the first event just after the fertilizer application in January 2013 decreased progressively to 1.7 mg L^{-1} during the following events. However, nitrate concentration peaked again (202 mg L^{-1}) just after the second application of fertilizer in March 2013, decreasing to very low concentration with following runoff events. This nitrate could accumulate and pollute downstream water bodies. Therefore, practices that help to reduce the initial nitrate concentration peak should be the goal of future research. Moreover, soil conservation based on minimum till and residues retention requires the use of herbicide. The runoff water samples analysed in 2013 to determine the presence of herbicides applied to the wheat crop grown in Plot I showed no traces of herbicide. Nevertheless, in order to achieve a long term view of the environmental impacts of irrigation and the soil conservation system adopted in the study catchment, the exportation of pesticides through the gauging station should be monitored routinely.

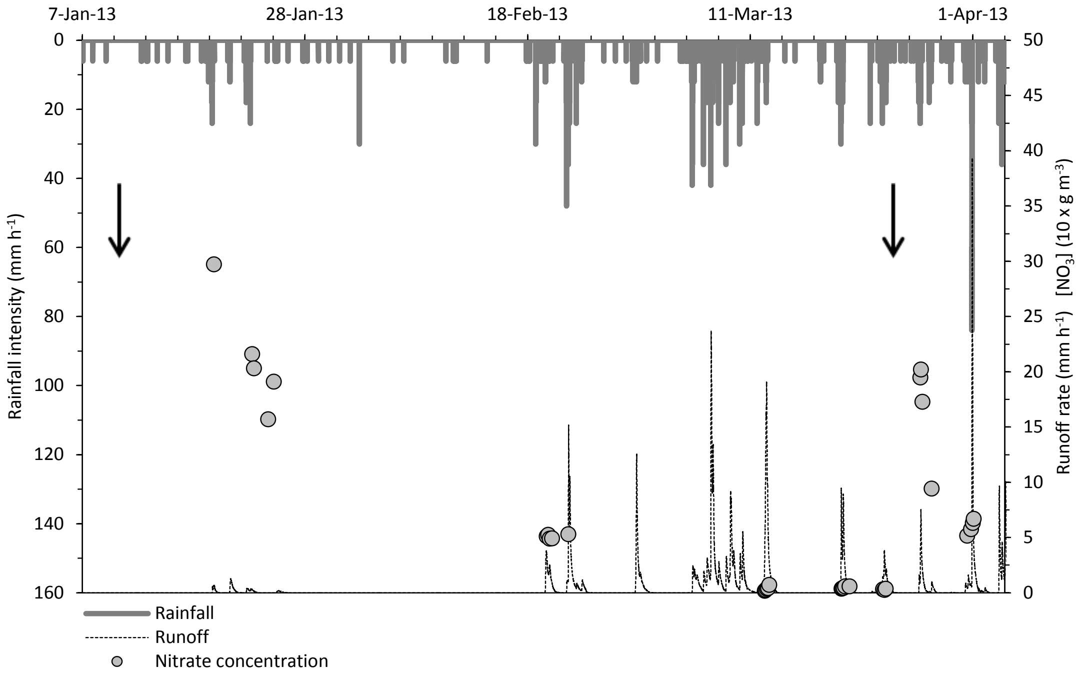

Figure 28. Runoff, rainfall and nitrate concentration ([NO$_3$]) in samples of runoff water from January to March 2013. The arrows indicate the dates of application of nitrogen fertilizer.

4.5. Conclusions

The hydrological effects of a novel set of soil conservation practices introduced by a pioneer farmer to grow irrigated annual crops in southern Spain were assessed at catchment scale. The study has shown, once again, the complexity of intervening factors that are further confused by the high variability of rainfall in Mediterranean environments. Comparison of runoff and sediment loss results with measurements made in a nearby catchment grown with olives, and with two catchments grown conventionally with annual crops in Navarra, did not allow drawing clear conclusions about the soil conservation advantages of the studied cropping system. A set of concluding remarks includes that much longer periods of study are necessary to achieve confidence in this kind of assessments, that catchment studies are essential to translate small-scale results to production farm scale, and that the type of hydrological station installed at the study catchment can provide valuable, integrated information for conservation effects assessment.

The amount of runoff for a given rainfall depth was highly determined by soil moisture at time of initiation of the rainfall event. This factor was more important than rainfall intensity computed for 30 minutes intervals. The amount of residues covering the soil surface had a clear and notorious effect reducing sediment losses. The set of soil conservation techniques evaluated in this study was more effective protecting the soil directly from water erosion than through the reduction of runoff. The practice of favouring spontaneous germination of wheat seeds to obtain an early cover/catch crop growing during autumn and early winter is highly recommendable to enhance this effectiveness. Therefore, the crop rotation selected is critical from the soil conservation point of view.

Irrigation can contribute to enhance productivity but also to conserve soil, through the production of straw biomass and the possibility of favouring with irrigation the growth of cover/catch crops. However, monitoring other adverse effects like nitrogen and herbicides runoff, linked to the intensity of irrigated farming systems, should become part of the conservation effects assessment.

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Chapter 5 - General discussion

5.1. Sustainability and conservation agriculture

The lack of sustainability of traditional farming systems concerning soil issues has led to the need of new agricultural paradigms focusing on the role played by labours and other forms of soil management play in the water, carbon and nitrogen cycle and in the emission of sediment and agrochemical residues clogging and polluting waterways and water reservoirs. At the same time, agricultural goods supply must be maintained and even increased due to increases in world population.

Conservation agriculture, under its different adopted forms, represents an attempt from farmers and researchers to achieve sustainability goals. Irrigated permanent bed planting systems with minimum or zero tillage and crop residues maintenance are capable to follow CA principles while maintaining yield and improving soil quality in different environments, including Mediterranean (Hulugalle and Daniells, 2005; Sayre *et al.*, 2005; Ram *et al.*, 2012).

5.2. Bed planting systems in southern Spain

As seen in Chapter 2, maize and cotton crops conducted from 2010 to 2012 in conventional (CB) and permanent (PB) bed planting systems with irrigation and controlled traffic in Córdoba, southern Spain, had the same tendency in terms of yield than for the short term since its adoption (2007-2009) (Boulal *et al.*, 2012). Maize yields were in the order of those expected for the region (RAEA, 2007). Regarding cotton crop, seed+lint yield were low in the three planting systems in 2011 (RAEA, 2006). It is important to highlight that, cotton crop in *La Parrilla* commercial farm (Chapter 4), conducted under low-input schemes hitherto (Boulal and Gómez-Macpherson, 2010), was grown in 2012 with more irrigation water and agrochemicals to achieve better yields due to higher international prices (FAO, 2013b). However, yield was not as high as targeted by the farmer that year, being in the order of the one obtained at the experimental plots in Alameda del Obispo farm (Chapter 2). The farmer blamed the poor cotton performance on seed quality problems due to a low demand since the drop that this crop is experiencing in the region (R. Calleja, personal communication).

Having been maize and cotton yields similar in CB, PB and the decompacted permanent bed system (DPB), the highest benefit will correspond to system requiring less input. In CB, DPB and PB systems, inputs level decreased in that order. However, gross margins for each crop must be calculated in order to reach a conclusion in economic terms not only qualitative but quantitative. In these calculus, however, not only extra labours in DPB and CB compared PB should be considered but the power that each labour required must be taken into account due to differences in soil compaction and efficiency of traffic. Beyond differences between the three planting systems in term of type or amount of operations, at the beginning of each growing season PB and DPB have the advantage of previous compaction in trafficked furrows, which would result in greater efficiency of the energy used during farming operations, for example sowing, when in CB recently made furrows have very loose soil and demand more tractor-power for transiting (Taylor, 1983). It should be added that, although the same sowing machine was used in the three systems during the study in Chapters 2 and 3, no-tilled soils usually require heavier ones and more tractor power to place seeds in a more compacted soil (Baker and Saxton, 2007) as, in general, drought requirement to shear soils increases with compaction (Chamen *et al.*, 1990; Chamen and Cavalli, 1994).

There were no consistent differences between CB, PB and DPB in terms of growth and crop yield. Therefore, tillage or compactions appear no to have significantly affected crop performance. What was observed is that wheel traffic compaction affected root growth. Apparently that did not compromise the development of biomass accumulation, at least compared with CB. Nevertheless, reductions of root system in compacted soils should be taken into account when designing strategies to improve fertilizers efficiency and reduce environmental risks: fewer roots will imply less use of nutrients applied with fertilizers, reducing fertilizer productivity and increasing the proportion of agrochemicals lost with drainage and runoff. Together with this, soil compaction can reduce nitrogen mineralization and increase gaseous nitrogen emission, in particular if soil moisture is close to saturation (Breland and Hansen, 1996; Gasso *et al.*, 2013).

Subsoiling of trafficked furrows in DPB did not contribute to crop root system development, at least in the soil layers and sites assessed. It should be asked whether this operation was really useful for the crop. On the one hand, subsoiling of trafficked furrows may reduce soil compaction, increase infiltration, and reduce runoff and consequent erosion. On the other hand, there are costs for subsoiling related not only with money expenditure but with soil coverage and soil organic matter loss: tillage requires an outcome and may be detrimental for the stability of soil structure and could foster erosion.

As seen in Chapter 2 and 3, tillage has effects on soil properties that remain in time and influence soil organic carbon dynamic, soil structure and compaction, and root growth. It would be interesting to assess whether, for the systems studied in both experimental plot (Chapter 2) and the commercial farm (Chapter 4), subsoiling techniques conducted to decompact the soil trafficked by machinery wheel can be improved in terms of zone, depth and frequency of performance, as indicated by (Raper *et al.*, 2007).

5.3. Crop residues, rotations and irrigation

In Spain (and Andalusia), approximately 50% of the straw biomass from winter cereals was baled in 2011, i.e., did not stay on-field (MAGRAMA, 2013). In the rest of cultivated surface, straw could be burned, buried by means of tillage operations, grassed or maintained covering soil surface, what implies a great uncertainty about the arable surface that maintains crop residues. On the other hand, no data is available regarding the use of spring crop residues.

It is important to highlight that large amounts of crop residues are not essential to achieve sustainability objectives; stable yields, adequate protection of soil surface or accumulation of soil organic carbon can be achieved even with partial retention of crop residues (Govaerts *et al.*, 2005; Verhulst, Kienle, *et al.*, 2010). Certain crop rotations (e.g. those including cotton) may be more suitable than others to reduce the pressure of crop residues on a farmland in certain cases, reducing disadvantages of managing high volumes of residues biomass. For example in *La Parrilla* farm, the sequence maize-cotton-wheat allows to meet economic and soil conservation goals by considering the gross margin of the entire rotation and, among others, the volume of crop residues generated and the length of fallow periods: the farmer looks for soil protection at critical periods (rainy winter) and to reach the time of a new sowing with a quantity and distribution of residues such as to not hinder soil drilling and seed placement by the seeder as well as to impede increases in populations of damaging invertebrates. To do the latter, the farmer grow cotton that contributes with relatively little plant residues and also uses the undulating topography created by the ridges that helps with moving residues towards the furrows, partially releasing beds.

Irrigation increases the range of crops that can be cultivated in a given area, and with this, the chances of using crop rotations. Moreover, irrigation may be seen as a diversification tool that could help meeting the third and most neglected of the three pillars of the AC: crop rotation. Besides of achieving the economic target of the farm, the possibility of growing a wide range of crops allows more control on ground coverage (by crop canopy and residues), facilitating farming operations and reducing erosion risk (Carter and Berg, 1991).

Despite the wide variety of crops used in the conservation agriculture systems of Córdoba province evaluated in this thesis (maize, cotton, wheat, sunflower, onion) none of the rotations included legumes. How would have progressed soil quality and yields if the rotations studied had incorporated legume crops? Indeed, examples in the literature in this regard are not abundant; Rochester (2011) reported higher SOC sequestration by including legumes in the rotation carried on permanents beds with minimum tillage.

5.4. Conservation agriculture and efficiency in crop production

As seen by means of this Thesis and the reviewed literature, compared with farming systems based on conventional tilled soil and monoculture, conservation agriculture in permanent bed planting systems with irrigation, maintenance of crop residues and controlled traffic offers the possibility of increasing the efficiency of resources in regard with:

- Fewer farming operations are required with saving of time and labour.
- Low pest pressure and need for pesticides due to crop diversification.
- Crop residues management is facilitated because they concentrate in furrows, releasing beds and allowing their heating and the placement of seeds during sowing.
- Crop residues and less tillage result in less CO2 emissions and an accumulation of soil organic carbon.
- Benefits associated with the highest concentration of soil organic carbon, including more stable soil structure, e.g. less erosion.
- Crop residues allow water harvest, not only by reducing evaporation but by reducing runoff and increasing infiltration and thus, increase in water availability for crop growth.
- Compaction concentrates in trafficked zones (furrows in the case of this Ph.D. Thesis), which allow maintain other areas free of traffic and compaction. Traffic confinement allows adopting precision tillage to undo compaction.

Some critical points that can reduce the efficiency in using resources in PB systems are:

- Large amounts of crop residues covering the soil with incidence on radiation use by crops: irregular sowing leading to poor plant stands and; delay in sowings and plant emergence due to crop residues impeding soil heating.
- Large amounts of crop residues covering the soil as a possible shelter for detrimental microorganisms and invertebrates that could reduce seedling emergence or lead to herbivory after crop establishment.
- Excess of soil moisture: higher risk of soil compaction during trafficking.
- Compaction: fewer roots grow in compacted soil; therefore there will be less use and greater potential for nutrients loss and pollution.
- Compaction: reduced infiltration and increased runoff water, less water, soil and nutrients available to growing plants.

5.5. More research is required

After the works conducted as part of this thesis, the need for further knowledge appears for two main reasons:

- to better understand the effect of subsoiling as a way to alleviate compaction, targeting this operation to that area of the soil profile where it has more effect and performing it when its profit on the crop and the entire cropping land (from hydrological point of view) is the greatest;
- to identify and quantify chemicals and other pollutants exported with runoff water from cropping lands, by evaluating critical periods for losses as well as agricultural techniques that mitigate these losses.

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Chapter 6 - General Conclusions

This Ph.D. Thesis allowed assessing an innovative planting system to grow annual crops in the Mediterranean environment: the permanent bed planting system with crop rotation, irrigation, crop residues maintenance, and controlled traffic of machinery wheel (PB). PB follows conservation agriculture principles to achieve on- and off- farm sustainability goals: optimize farm productivity while maintaining productive and environmental resources to future generations and providing externalities such as carbon sequestration and landscape enhancement.

Compaction of soil and stubble presence and accumulation in agricultural parcel, two of the main problems faced by farmers when adopting the farming practices included in CA, were at the focus of attention of this Thesis.

Soil compaction in PB increased in the mid-term since the adoption of this set of farming practices. However, crop yields were not affected by the condition of soil compared to less compacted conventionally prepared bed system (CB). It must be highlighted that the PB system is simpler than the CB in operations: soil preparation in PB may be delayed until the elevation of the beds allow the sowing line freeing excess stubble and ensure sufficient accumulation heat to ensure rapid germination and crop emergence.

The controlled traffic strategy collaborated in confining tractor wheel pass and compaction in permanent lanes, avoiding random traffic, i.e., implausible to be controlled, compaction. It is necessary more effort to study and improve the practice of located decompaction as practiced in this study in furrows with traffic in both experimental plot (Chapters 2 and 3) and commercial plot (Chapter 4) to know its limitations in terms of benefits for crops (to foster root systems development) or for the overall cropping land (in terms of hydrology, CO2 emissions and carbon sequestration).

Crop residues, if properly managed, not only did not impede farming practices or crop performance but was a key component of PB systems, protecting soil surface and enabling soil organic carbon accumulation at first soil layers.

At catchment scale (Chapter 4), the study of a commercial PB system close by the experiment conducted and assessed in Chapters 2 and 3, has shown the complexity of intervening factors confused by the high variability of rainfall in Mediterranean environments. Nevertheless, this type of research is essential for translating small-scale results to on-farm scale. Runoff in the catchment depended on soil moisture at the beginning of a storm and on the intensity of the rainfall. The soil protection by crop canopy and residues was effective in reducing sediment losses. Commercial PB system was relatively more effective in reducing erosion than in preventing runoff. The cover crop obtained by fostering wheat seeds left after harvest, both standing and lying on the ground as a mulch after its chemical weeding, offered protection during the rainy season, which confirms that appropriate rotations and agricultural managements are imperative for soil conservation.

On the whole, permanent bed planting systems with crop rotation, irrigation, crop residues maintenance, and controlled traffic, allow practicing agriculture in a sustainable manner in the Mediterranean environment, improving soil quality, sequestering carbon and reducing erosion risk.

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