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Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain

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ABSTRACT

Rainfall, runoff and soil loss from 6 m × 12 m plots were recorded during 7 years (2000–2006) in an experiment in which three different soil management systems were compared in a young olive grove installed on a heavy clay soil, near Cordoba, Southern Spain. The no-tillage (NT) system, kept weed-free with herbicides, had both the largest soil loss (6.9 t ha^{-1} year^{-1}) and the highest average annual runoff coefficient (11.9%). By contrast, a cover crop (CC) of barley, reduced the soil losses to 0.8 t ha^{-1} year^{-1} and the average annual runoff coefficient to 1.2%. Conventional tillage (CT), had intermediate values of soil loss (2.9 t ha^{-1} year^{-1}) and an average runoff coefficient of 3.1%. The different treatments were established 4 years after planting the olive trees, and a significant decrease in soil and runoff losses was observed with time as the olive trees grew and their canopies developed. Measurements at the end of the experiment showed a significant improvement in the topsoil properties of the CC treatment as compared to CT and NT. The soil under NT presented a significant degradation with respect to traditional CT management. Organic matter values were 2.0, 1.4 and 1.0%, and stability in water of macroaggregates was 0.452, 0.418 and 0.258 kg kg^{-1} for CC, CT and NT, respectively. These results indicate that the use of a cover crop can be a simple, feasible soil and water conservation practice in olive groves on rolling lands in the region. A key factor in its practical use is to establish it early enough to protect the soil in the critical initial years of the grove, when most of the soil is unprotected by the small olive canopy.

1. Introduction

Olive is one of the most emblematic crops in Spain, and especially in Andalusia, its southernmost region. Andalusia is the main olive cultivation area in the world as it produces 39% of the world's olive oil and 24% of the table olive production (average figures of the period from 2000 to 2003 given by Consejería de Agricultura y Pesca, 2006; International Olive Oil Council, 2006). This production is achieved in Andalusia by devoting 17% of its total area to the olive. The olive crop represents 25% of the value of the Andalusian agrarian production (CEH-JA, 2006). Although commercial olive cultivation has been present in Andalusia since Greek and Roman times (Semple, 1931, Chapter XIV), its current position as the most important single soil use in Andalusia has been reached through several eras of expansion, from the second half of the 16th century to the early decades of the 20th century (Guzmán, 2005). Historically, olive cropping has been concentrated on hilly lands, where olive trees had to adapt to shallow, stony soils, and to dry conditions, whereas herbaceous crops were cultivated in flat areas with more fertile soils. This explains why, despite a recent trend towards new, more intensive plantations in valley areas, most olive groves in Andalusia are rainfed and planted in sloping areas. To date, 31% of the olive acreage in Andalusia is located on very steep terrains, on slopes of above 15%; 38% of the acreage is on moderate slopes, in the 7–15% range; the rest on slopes of under 7%. Only 16% of the olive acreage in Andalusia is on slopes of below 5% (Consejería de Agricultura y Pesca, 2003). Traditional olive production is based on low tree densities, i.e. about 100 trees ha^{-1}, weed control via frequent tillage and canopy size limited by pruning, to ensure the productivity and survival of the plantation in a limited rainfall environment. These features contribute to understanding why olive production in the region has been associated with severe soil erosion problems (Gómez et al., 2003) accompanied by fertility depletion and loss of biodiversity (Beaufoy, 2001), that worsened with the arrival of farm mechanization in the early 1960s.

Alternative soil management practices to conventional tillage, hereafter CT, have been developed, partially encouraged by the

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concern raised by water erosion (Pastor et al., 1999). These alternatives consist basically of no-tillage with herbicides to maintain a bare, weed-free soil, hereafter, NT; or the use of a cover crop grown during autumn and winter, either sown in early autumn or obtained via regeneration of the natural vegetation after the onset of rains, hereafter, CC. The cover crop is controlled by tillage, mowing or spraying with herbicide in early spring to prevent competition with the olive tree for water and nutrients.

Several studies have reported the use of runoff plots to evaluate soil erosion in mature olive groves. Raglione et al. (1999), in Southern Italy, measured total soil losses of 0.36 and 41 t ha^{-1} $year^{-1}$ for CC and CT, respectively, in a 2-year plot experiment. Kosmas et al. (1996) measured annual soil losses between 0 and 0.03 t ha^{-1} $year^{-1}$ in semi-natural olive groves in Greece with 90% of the soil covered by vegetation. In a 2-year study in Andalusia, Spain, Francia et al. (2006) measured soil losses of 25.6, 2.1 and 5.7 t ha^{-1} from NT, CC and CT, respectively. Also in Andalusia, Gómez et al. (2004) reported average soil losses of 8.5, 1.2 and 4.0 t ha^{-1} from NT, CC and CT in a 3-year experiment on a heavy clay soil, and Gómez and Giráldez (2007) reported average soil losses of 21.5 and 0.4 t ha^{-1} for CT and CC in a different 4-year experiment. Bruggeman et al. (2005) measured average soil losses of 41.4 and 11.2 t ha^{-1} $year^{-1}$ in orchards under CT and CC, respectively, in Syria in an area with a slope of 24% for a 4-year period. Even though the results of all these trials support the use of CC over other soil management practices for reducing runoff and soil loss, many of them had a limited duration (4 years at the most).

The effect of soil management on soil properties in olive orchards has been assessed in a few studies conducted in commercial farms (e.g. Álvarez et al., 2007, 2008; Milgroom et al., 2007; Soria et al., 2005; Hernández et al., 2005; Gómez et al., 1999; Vanderlinden et al., 1998). In general, these studies detected an improvement in the infiltration rate and in the organic matter content in the top soil of groves under CC management.

Despite the work described above, long-term studies that evaluate simultaneously the effects of different soil management on soil properties and on soil and runoff losses in olive groves are, to our knowledge, lacking. The results of a 7-year study in which the effects of three soil management methods on soil properties and on runoff and sediment losses were measured in a commercial olive orchard are presented here.

2. Methods

In 1999, a field experiment was established at ''La Conchuela'' farm, at 10 km west of Cordoba, Spain, 37°48′54″N 4°53′53″W and at 147 m above sea level. The plantation was installed in 1993 with trees at 6 m × 7 m spacing, although about 40% of the trees had to be replanted after a severe infection by *Verticillium dahliae*, associated with prolonged soil waterlogging in the spring of 1996. The trees were drip-irrigated. The average annual rainfall is 655 mm with 77% concentrated in the October–March period. The soil, formed on Miocene marls, has been classified as Typic Haploxerert (Soil Survey Staff, 1999), or Vertisol according to the FAO classification. It has an Ap horizon 0.45 m deep, with 49% clay and 47% silt content and 1.07% OM in 1998 (Ramírez, 1998), with a very fine granular structure. The subjacent horizon is an AC horizon, 0.45–1 m deep, with 46% clay and 46% silt and 0.5% OM with a prismatic structure. The C horizon from 1 m downwards has 44% of clay and 45% of silt and 0.3% OM. These soils are highly plastic when wet, and crack as they dry.

Nine closed runoff plots were established. Each plot was 6 m wide and 12 m long with the long side along the direction of the maximum slope. Each plot enclosed two trees that were aligned along the direction of the maximum slope in the centre of the plot. Both trees were 3 m away from each of the two longest (12 m) plot edges, with the first tree 3 m away from the outlet, and the second 9 m away from the same outlet. The average plot slope was 13.4%. The particle size distribution of soil in the nine plots was homogeneous. All the plot soils belonged to the silty clay texture class.

The runoff generated on each plot was collected and measured with a system of tipping-bucket gauges similar to that of Barfield and Hirschi (1986) with a 1-min resolution. A barrel located upstream of the tipping buckets acted as a sediment trap and the sediment concentration of the runoff collected in the barrels was used to calculate soil loss. Rainfall was measured with two gauges; one connected to a data-logger that recorded intensity at 1 min intervals, while the other, a cup-shaped gauge, measured total rainfall. The experiment was set up during 1999 and early 2000 when the different soil management treatments were established. Regular collection of runoff and sediment started on 1 September 2000. Since 1 September 2003, the average sediment concentration in the runoff downstream of the sediment traps was measured using a collection system based on that of Khan and Ong (1997) that collected runoff samples from each plot. After installing this system, the efficiency of the sediment traps was estimated by Eq. (1) (Gómez et al., 2004). The correction in Eq. (1) was applied to the soil loss measured for the period prior to September 2003,

$$SL_T = 1.4\, SL_{st} \qquad r^2 = 0.88 \tag{1}$$

where SL_T is the total sediment loss (calculated adding the sediment in runoff to the sediment in trap) and SL_{st} sediment loss calculated using the sediment trap. The efficiency of the traps was similar for all the plots and treatments. Runoff and sediment measurements ended in February 2006, because normal farming operations interfered with the maintenance of the runoff plots.

The experiment design consisted of three soil management systems replicated three times in a completely randomized block. The three soil management treatments were no-tillage, conventional tillage, and cover crop. NT consisted of maintaining the soil weed-free and bare with herbicide applications. The herbicide applied was glyphosate (Piton™, 0.36 kg a.e. L^{-1}, Dow AgroSciences™) at 2.1 kg a.e. ha^{-1} using a backpack sprayer that delivered a spray volume of 350 l ha^{-1}. This was done depending on the weed growth all through the season, and added up to between 3 and 5 applications per year, mostly concentrated in fall and spring. Conventional tillage, consisted of three to four passes, 0.15 m deep, with a rotary tiller (5.5 h.p.) per year, starting after the first rain in late September or early October to control weeds in the whole plot. The crop cover consisted of two strips (2 m wide and 12 m long each) of barley sown in October and killed with herbicide in early April, leaving the crop residue on the surface. The barley strips were sown parallel to the plot's longest edges, while a 2 m wide central strip across the plot (where the two trees were located) was maintained with bare soil using the same herbicide applications as in the NT treatment. Every year, a 0.1-m deep rotary tiller cultivator pass prepared the seedbed before sowing the barley. Soil management operations were maintained in the three treatments until June 2006.

In the second half of June 2006 soil samples were collected at two points at two different depths (0–5 and 5–10 cm) from each plot, always outside the tree canopy area. They were air dried, crumbled and passed through a 2-mm sieve for the determination of nine chemical and physical properties, two in the field and seven

Table 1
Methods used in field and laboratory measurements, *n* indicates the number of replications per treatment and depth

Parameters	Method	n[a]
Field measurements		
Olive canopy dimensions	Estimating tree radius from pictures	4
Bulk density ($Mg\ m^{-3}$)	Cylindrical core sampler[b]	6
Final infiltration rate	Rainfall simulator[c]	6
Laboratory analysis		
Particle size distribution	Hydrometer method (Gee and Bauder, 1986)[d]	6
Water stable macroaggregates ($g\ kg^{-1}$)	Protocols of Barthes and Roose (2002)[e]	24[a]
Organic C (%)	Walkley-black method (Nelson and Sommers, 1982)	6[a]
Organic N (%)	Kjekdahl method (Stevenson, 1982)	6[a]
Extractable P ($mg\ kg^{-1}$)	Olsen method (Olsen and Sommers, 1982)	6[a]
Exchangeable K ($mg\ kg^{-1}$)	Ammonium acetate method (Knudsen et al., 1982)	6[a]
CEC ($mol_c\ kg^{-1}$)	Ammonium replacement method (Rhoades, 1982)	6[a]
Soil respiration ($mg\ CO_2\ kg^{-1}$)	OxiTop control method (Vähäoja et al., 2005)[f]	3

[a] Number of replications per depth interval (0–10 cm and 10–20 cm).
[b] Core 5.0 cm diameter, 5.0 cm high.
[c] Measured over an area of 1.0 m × 0.7 m in a simulation experiment that lasted 60 min since onset of runoff at 65 mm h^{-1} rainfall intensity. The rainfall simulator used is described in Alves et al. (2008).
[d] Coarse sand (2.0–0.1 mm) and fine sand (0.1–0.05 mm) were separated by wet-sieving.
[e] Water-stable (WS) aggregates separated into WS-microaggregates (<0.02 mm), and WS-macroaggregates (>0.25 mm) on a coarse-sand free basis (>0.25 mm).
[f] 100 g of soil (dry weight) moistened to 50% of soil water-holding capacity and 50 mL beaker filled with a 1 M NaOH solution in an incubation cabinet at darkness and 20 °C for 1 day (WTW, Weilheim, Germany). Measured in the top depth interval (0–10 cm) only.

in the laboratory. Table 1 describes the properties and the methodology followed for their determination. On the same dates, rainfall simulation experiments were performed also outside the canopy, in areas of the plots that had been moistened previously to field capacity ($0.344 \pm 0.009\ m^3\ m^{-3}$) using the drip irrigation system of the orchard. The rainfall simulator used, covering an area of 0.9 m^2, has been described in Alves et al. (2008). Soil bulk density was measured in standard core-extracted samples taken in the moistened areas.

3. Results

Fig. 1 shows the bimonthly runoff coefficients (runoff as % of rainfall) measured in the three treatments during the experiment. The data plotted in Fig. 1 have two main features. First, there is a clear difference in the runoff yield of the different treatments, with NT having the highest runoff coefficient and CC the lowest. Treatment differences were significantly different most of the years, as shown in Table 2. Runoff was concentrated from November to March, the months of the highest rainfall and when the soil was moist after the dry season. There was also an apparent decreasing trend in runoff as the experiment progressed, especially in NT that initially had the highest runoff coefficient, Fig. 1 and Table 2. Tree canopies increased in size as the experiment advanced, starting with 11% ground cover at the beginning of the experiment, and increasing to 23 and 38% in 2003 and 2005, respectively, with no apparent differences between treatments. The evolution of sediment loss followed the same pattern as runoff

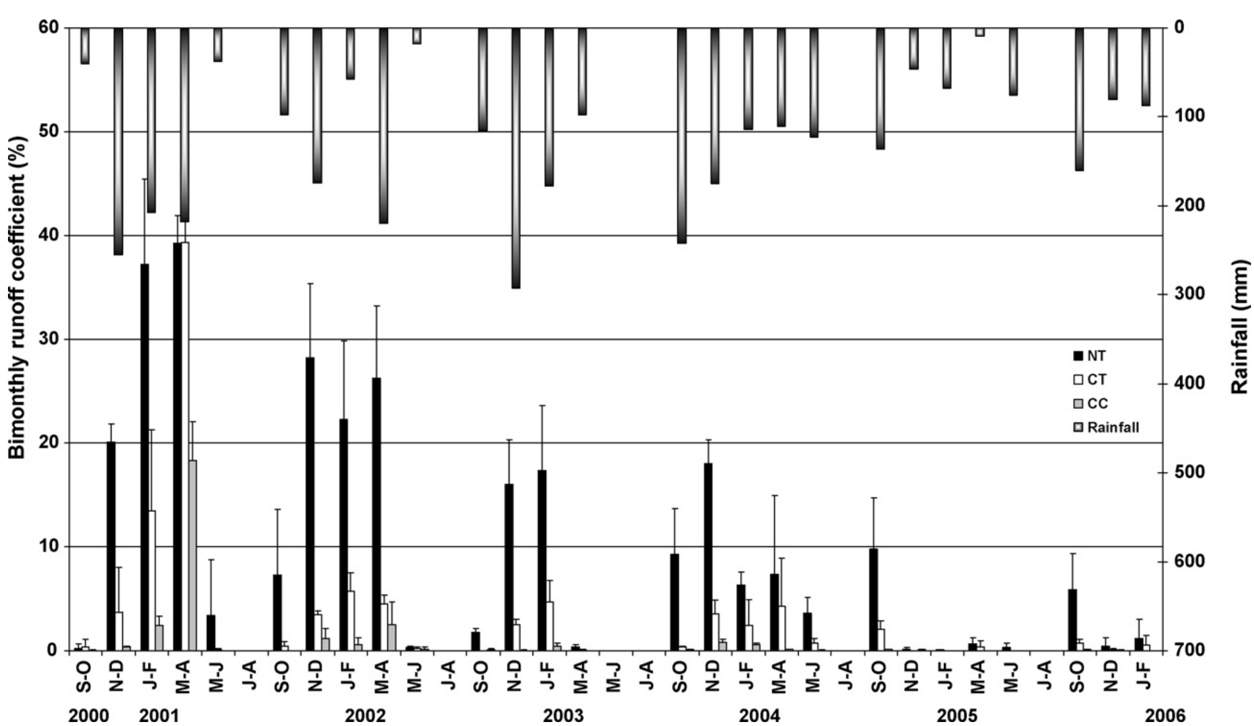

Fig. 1. Average bimonthly runoff coefficient for the three soil management methods. Error bars are ±standard deviation.

Table 2
Annual average runoff coefficient, and sediment loss for the hydrological years starting 1 September 2000 until 15 February 2006

	Rainfall (mm)	Treatment	Runoff Coefficient (%)	Runoff yield (mm)	Sediment loss (t ha^{-1} $year^{-1}$)
2000–2001	744	NT	35.9C	267.1	18.8B
		CT	18.4AB	136.9	14.1B
		CC	6.2A	46.1	4.5A
2001–2002	594	NT	18.2C	108.1	15.4C
		CT	1.6AB	9.5	2.0AB
		CC	1.1A	6.5	0.6A
2002–2003	656	NT	10.4C	68.2	1.7C
		CT	2.1B	13.8	0.2AB
		CC	0.2A	1.3	0.1A
2003–2004	768	NT	8.9C	68.4	4.1C
		CT	1.9AB	14.6	0.4B
		CC	0.3A	2.3	0.1A
2004–2005	331	NT	4.2C	13.9	0.7A
		CT	0.9B	3.0	0.5AB
		CC	0.1A	0.3	0.03A
2005–2006[a]	369	NT	2.9C	10.7	0.8C
		CT	0.5B	1.8	0.2BA
		CC	0.1A	0.4	0.02A
2000–2006[†]	577	NT	11.9	78.2	6.9
		CT	3.1	25.9	2.9
		CC	1.2	8.2	0.8

Values followed by the same letter are not significantly different for the Student–Newman–Keuls' range test at $P < 0.05$. NT is no-tillage, CT is conventional tillage, and CC is cover crop soil management.
[a] Incomplete year, ending on 15 February 2006.
[†] Average values.

losses, Fig. 2 and Table 1, with significant differences between treatments most years. The NT treatment caused the largest soil losses, and averaged 6.9 t ha^{-1} $year^{-1}$. The CC treatment presented the smallest soil losses, 0.8 t ha^{-1} $year^{-1}$, while the average soil loss in the CT treatment for the same period was 2.9 t ha^{-1} $year^{-1}$. It is also apparent from the experiment data (Fig. 2 and Table 2) that there was a decrease in sediment losses over the time, especially in NT and CT treatments.

Table 3 presents the management-induced changes in soil properties measured after 7 years of different treatments. There were significant differences in OM between treatments, with CC having the highest values and NT the lowest. Organic N, exchangeable P, and the C:N ratio followed a similar pattern. In all cases, the major changes were in the top 5-cm, although this was less evident in the CT treatment. The NT treatment presented the lowest values of extractable P, which was higher in CT than in

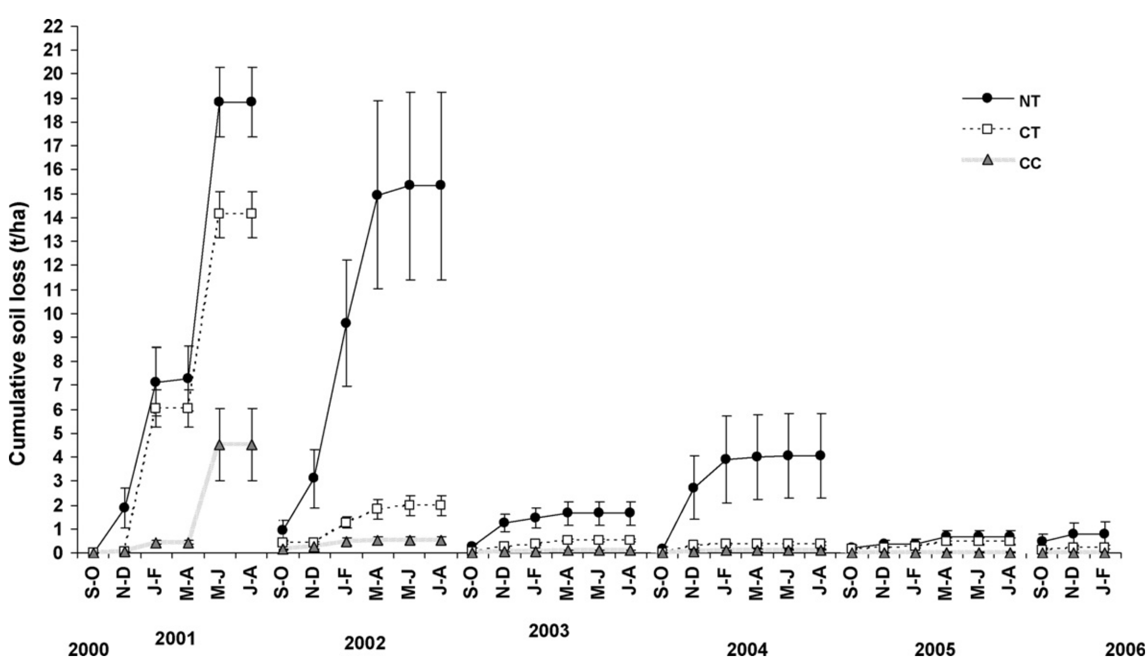

Fig. 2. Average annual soil loss for the three soil management methods. Error bars are ±half the standard deviation.

Table 3
Values of soil properties for the three soil management treatments and two soil depths

Parameters	Soil management						Factor		
	No-tillage (NT)		Cover crop (CC)		Conventional tillage (CT)		Management	Depth	Management × depth
	0–5[a]	5–10[a]	0–5[a]	5–10[a]	0–5[a]	5–10[a]			
Physical parameters							ANOVA *P*-value		
Bulk density (Mg m^{-3})	1.48 ± 0.05	1.54 ± 0.05	1.36 ± 0.07	1.46 ± 0.07	1.38 ± 0.02	1.50 ± 0.04	**0.000**	**0.000**	0.589
Clay (%)	49.1 ± 5.8	50.3 ± 6.4	52.6 ± 4.0	54.5 ± 3.2	50.3 ± 6.4	54.0 ± 2.5	*0.070*	0.429	0.955
Silt (%)	47.4 ± 6.2	46.4 ± 5.7	44.0 ± 2.5	42.5 ± 1.7	46.4 ± 5.7	43.0 ± 2.9	**0.044**	0.670	0.839
Sand (%)	3.5 ± 0.9	3.3 ± 0.9	3.4 ± 1.7	3.1 ± 2.1	3.3 ± 0.9	3.1 ± 1.0	0.758	0.216	0.628
Fine sand (%)	2.0 ± 0.9	1.9 ± 0.5	1.8 ± 0.8	1.5 ± 1.7	1.9 ± 0.5	1.9 ± 0.4	0.202	0.161	0.415
WS-macroaggregate (g kg^{-1})	258 ± 59.5	333 ± 50.1	452 ± 30.7	524 ± 132	418 ± 68	420 ± 95.6	**0.000**	*0.074*	0.463
WS-microaggregate (g kg^{-1})	0.127 ± 0.02	0.073 ± 0.009	0.088 ± 0.018	0.079 ± 0.024	0.099 ± 0.018	0.094 ± 0.024	0.144	**0.002**	*0.008*
Infiltration rate (mm h^{-1})	11.2 ± 1.7	n.a.	23.4 ± 4.1	n.a.	8.9 ± 3.2	n.a.	**0.000**	n.a.	n.a.
Chemical parameters									
Organic matter (%)	1.04 ± 0.27	0.78 ± 0.20	2.03 ± 0.24	1.17 ± 0.18	1.36 ± 0.27	1.18 ± 0.23	**0.000**	**0.000**	*0.005*
Organic N (%)	0.08 ± 0.01	0.06 ± 0.01	0.11 ± 0.01	0.08 ± 0.01	0.09 ± 0.02	0.08 ± 0.01	**0.001**	**0.003**	0.123
Extractable P (mg kg^{-1})	8.07 ± 1.55	4.18 ± 0.57	11.9 ± 3.43	8.14 ± 3.18	14.2 ± 5.16	10.4 ± 4.27	**0.001**	**0.003**	0.999
Exchangeable K (mg kg^{-1})	464 ± 86.2	370 ± 65.1	690 ± 35.9	517 ± 21.4	655 ± 69.0	565 ± 113	**0.000**	**0.000**	0.360
CEC (mol_c kg^{-1})	0.230 ± .0271	0.218 ± .0136	0.233 ± 0.0218	0.242 ± .0251	0.259 ± .0489	0.242 ± .0265	0.109	0.494	0.554
C:N ratio	22.4 ± 4.08	21.1 ± 4.58	30.7 ± 1.24	25.5 ± 4.61	26.2 ± 2.22	26.0 ± 3.71	**0.001**	*0.084*	0.262
Biological parameters									
Soil respiration (kg CO_2 kg^{-1})	0.452 ± .086.0	n.a.	1.01 ± .404	n.a.	1.11 ± 0.472	n.a.	0.255	n.a.	n.a.

Numbers are mean values ± standard deviation, followed by two-way, soil management and depth, analysis of variance (ANOVA) of soil properties. *P*-values in bold and in italics indicate statistically significant differences, with $P \leq 0.05$ and $P \leq 0.1$, respectively. n.a. = not available (the parameter was measured only in the surface soil layer, 0–5 cm depth).
[a] Soil depth (cm).

the CC treatment. There were no differences in CEC between the three treatments, since the changes in OM content were not important enough to modify this property in this soil with its high clay content. Despite the differences in the average values of soil respiration (Table 2), there were no statistically significant differences due to the large variability encountered in this parameter. The soil under NT was significantly more compacted than in the other two treatments. This treatment also presented significantly fewer WS-macroaggregates than CT and CC. There was an appreciable stratification in compaction and WS-aggregation between the two soil layers sampled. CC treatment gave a higher final infiltration rate than CT and NT, which had similar values, although the initial infiltration rates during the simulations were higher in the CT treatment compared to the CC treatment (data not shown). Several soil properties were significantly correlated with each other, see Table 4. Organic matter correlated positively with four other properties: organic N, $K_{avail.}$, WS-macroaggregates, and final infiltration rate. OM also showed a negative correlation with bulk density. Soil respiration was significantly correlated with WS-macroaggegates.

4. Discussion

The average annual runoff losses measured in this experiment were within the range measured in other studies in olive orchards, and exhibited a similar trend. Francia et al. (2006) measured, in a loamy soil on a 30% slope, higher runoff coefficients in the treatment under NT, 5.3%, and lower values for CT and CC, 1.5 and 2.7%, respectively, Bruggeman et al. (2005) measured average runoff of 184 and 66.5 mm $year^{-1}$ for orchards under CT and CC, respectively, in Syria, in an area with an average annual precipitation of 400 mm $year^{-1}$, Gómez and Giráldez (2007), in a sandy-loam soil on a 11% slope, measured runoff coefficients of 20 and 5.7% for CT and CC, respectively, and Raglione et al. (1999) reported runoff coefficients of 3.5 and 12.8% for CC and CT, respectively, in southern Italy. The lower runoff coefficient in the CC treatment in the experiment described in this paper might be explained by the higher infiltration rate induced by the cover crop in the area sown annually (2/3 of the plot area) compared to the CT and NT treatments. This increase in infiltration rate associated with CC management has been reported in other olive orchards (Romero et al., 2007). Differences in the runoff coefficient between CT and NT can be explained not by the final infiltration rate values after intense rainfall events, shown in Table 3, but to the higher infiltration rate and surface storage due to increased surface roughness in the weeks after each of the four tillage passes: this has also been reported in other olive orchards by Romero et al. (2007). In the experiment described in Gómez and Giráldez (2007), the trees also covered a small fraction of the soil surface which was significantly more compacted in the CC treatment than in this experiment, and had a much lower stability in water of its macroaggregates that must have caused a faster sealing of the tilled soil under rainfall. Runoff losses decreased throughout the experiment, especially under the NT management treatment. Several studies have noted that the infiltration rate in olive orchards is spatially varied, and that the area beneath the canopy tended to show a high infiltration rate regardless of the soil management (see for instance Romero et al., 2007 or Castro et al., 2006). During the five and half years of runoff measurements the ground covered by the canopy increased from 11 to 38%. The apparent decrease in runoff losses observed is what could be expected from an overall increase in average infiltration rate and hydraulic connectivity of overland flow along the plot associated with tree growth. This growth could, at least partly, explain the evolution of runoff coefficients, although there may be other sources of variability coupled with the year to year differences, such as variations in rain depth, and the intensity and occurrence of large events. In the case of CT and CC treatments, the effect was less marked probably because of the lower runoff generation of these treatments. In the case of the CC treatment, the progressive improvement of soil properties must have played a role in the decrease of the runoff coefficient.

The average annual sediment losses during the course of the experiment were within the reported range of other studies in

Table 4
Correlation matrix of the soil properties measured in the top soil (0–5 cm)

	$K_{avail.}$	$P_{avail.}$	N_{org}	CEC	OM	C:N	Soil respiration	Macroaggregate	Microaggregate	b.d.	Clay	Silt	Sand	Infiltration rate	Fine sand
$K_{avail.}$	X	r^2 = 0.418 p = 0.005 +	r^2 = 0.382 p = 0.008 +		r^2 = 0.507 p = 0.005 +	r^2 = 0.417 p = 0.005 +	r^2 = 0.532 p = 0.04 +	r^2 = 0.515 p = 0.001 +		r^2 = 0.517 p = 0.092 −	r^2 = 0.327 p = 0.021 +	r^2 = 0.396 p = 0.009 −			
$P_{avail.}$		X													
N_{org}			X		r^2 = 0.833 p = 0.000 +	r^2 = 0.286 p = 0.027 +				r^2 = 0.363 p = 0.052 −					
CEC				X							r^2 = 0.421 p = 0.007 +	r^2 = 0.560 p = 0.001 −			r^2 = 0.309 p = 0.03 +
OM					X	r^2 = 0.678 p = 0.000 +		r^2 = 0.371 p = 0.009 +		r^2 = 0.376 p = 0.0089 −				r^2 = 0.391 p = 0.007 +	
C:N						X		r^2 = 0.371 p = 0.000 +	r^2 = 0.384 p = 0.008 −	r^2 = 0.384 p = 0.008 −					
Soil respiration							X	r^2 = 0.501 p = 0.048 +	r^2 = 0.434 p = 0.075 −						
Macroaggregate								X	r^2 = 0.60 p = 0.000 −	r^2 = 0.453 p = 0.003 −					
Microaggregate									X						
b.d.										X					
Clay											X	r^2 = 0.954 p = 0.000 −			
Silt												X			
Sand													X		r^2 = 0.789 p = 0.000 +
Infiltration rate														X	
Fine sand															X

b.d. means bulk density, + means positive and − negative correlation between both variables. r^2 is the coefficient of determination of the linear regression between both properties, and p is the p-value of the Boferroni probability of the statistical significance of the linear correlation. Only correlations between variables with $p < 0.1$ are indicated.

olive orchards. Francia et al. (2006), in a loamy soil on a 30% slope, measured higher losses, 25.6, 5.7 and 2.1 t ha^{-1} $year^{-1}$ values for NT, CT and CC treatments, respectively, Raglione et al. (1999), in southern Italy, measured total soil losses of 0.36 and 41 t ha^{-1} $year^{-1}$ for CC and CT, Bruggeman et al. (2005) measured average soil losses of 41.4 and 11.2 t ha^{-1} $year^{-1}$ in orchards under CT and CC, respectively, in Syria in an area with a slope of 24%, and Gómez and Giráldez (2007) reported average soil losses of 21.5 and 0.4 t ha^{-1} $year^{-1}$ for CT and CC, respectively, on an 11% slope. The steeper slope or the greater length, sometimes both, of the plots used in these studies can be one of the reasons for the greater losses measured in many of the above studies compared to the experiment discussed here. The lesser soil loss measured in the CC treatment, compared to CT and NT could be due to a combination of lower runoff coefficient, increased ground cover and improvement of soil stability, see Table 4. The greater loss in NT, compared to CT and CC, can be explained by the higher runoff coefficient, the reduced stability in water of soil aggregates, and absence of any protection on the soil surface.

The decrease in sediment production throughout the duration of the experiment, which followed a similar reduction in runoff, can be explained by the same reasons discussed above for the runoff reduction. These results can provide some insight into the erosion risk from different situations in olive orchards. The initial years, 2000–2002, may be representative of a situation occurring in young plantations, or in mature plantations with few sparse trees. Under these conditions, the results presented in this paper suggest that the soil losses under NT or CT management are unsustainable as they are well above the limit of 1 t ha^{-1} $year^{-1}$ suggested by Jürgens and Fander (1993) to prevent a negative impact on soil quality and the latter's long-term sustainability. This has been true even in plots with a shorter slope length than the ones observed in many field situations, and for which greater soil losses could be expected, as indicated by the comparison above with other published runoff plot studies. The results observed in the CC treatment indicate that sediment losses under this management approach sustainable values, even assuming that at a field scale and longer slope length they should be slightly higher. One of the main concerns of farmers with respect to the use of cover crops in olive groves is the risk of competition for soil water and nutrients between the tree and the cover crop. This risk is minimal in the initial years of a plantation, when trees are small, or where tree densities are very low. This is also true in the case of irrigated groves that are adequately fertilized.

The results presented in this study underline the importance of establishing a cover crop at the time of planting to minimize soil loss in those critical years when canopy coverage is scant. Even in intensive plantations, where canopy coverage is high, sediment losses can be significant under bare soil management (CT or NT) with a potential effect on soil quality and its long-term sustainability. Intensive plantations in the region can be defined as being orchards with a tree density of over 100 tree ha^{-1} typical of traditional plantations. Most recent plantations in the region lie within this definition and have a tree density ranging from 160–400 tree ha^{-1}, although some are planted at 1500–2000 tree ha^{-1}. Although this conclusion is based on only 7 years of data and results may change over a longer time period, it should be noted that the impact of soil management on soil quality does not only depend on sediment losses, and this is discussed further on. The results of this study recommend the use of a CC system in mature plantations with a very low ground cover in order to achieve sustainable management from the water erosion standpoint. The NT treatment, bare soil with herbicide, does not benefit soil and water conservation compared to the traditional, CT, or the innovative, CC, in the region. The moderate runoff and soil losses measured under the CT treatment once the trees reached a significant ground cover area suggest that there is room for a combination of CT and CC management in areas with a moderate slope, or in soils with compaction problems. Examples of this combination could be killing the cover crop in early spring through tillage, or limiting tillage to one pass in spring allowing the natural vegetation to grow in fall and winter. These two practices have been documented in the region (Álvarez et al., 2007, 2008) in olive orchards.

The analysis of the topsoil properties of the experiment plots indicated outstanding differences in chemical properties between the various treatments. The one with the lowest values of nutrients and organic matter was NT. For this treatment, C_{org}, N_{org} and P_{ext} values were low in comparison to the values recommended for olive cultivation in the region (García et al., 2004). CC and CT presented higher nutrient contents within or close to the recommended values for the region (García et al., 2004). Only the CC treatment reached the 2% organic matter content in the top 5 cm, a value recommended for the region as a target for organic matter content in integrated production systems (Consejería de Agricultura y Pesca, 2002), which suggests that this reference value should not be regarded as a short-term objective by those regulating this production system in the region. All the treatments presented relatively high CEC values due to the high clay content of the soil. The CC treatment can be classified as being of a moderately rapid infiltration according to the USDA (1999) classification. NT and CT were both of a moderate infiltration, according to the same classification, due to a combination of consolidation and surface sealing, with the consolidation being more intense in the NT treatment. Stability in water of the macroaggregates followed a decreasing trend from CC to NT. WS-macroaggregates values in CC were within the range of the higher values reported by Barthes and Roose (2002) and Álvarez et al. (2007) in similar soils in France and Spain, respectively, while CT was in the medium and NT in the lower range, respectively, of those reported by the same authors. There is a trend towards decreased OM, WS-macroaggregates, final infiltration rate, and increased consolidation with NT compared to the CT treatment, with a statistically significant correlation of the OM content with the other three properties, see Table 4. Apart from the positive effect of OM on soil structure, this correlation is a consequence of the greater compaction and lower biomass input to the soil under CC than under CT and NT systems.

Gómez et al. (2004) reported values for some of the soil properties discussed above after 4 years of the experiment in the same plots. The trends observed after 4 years were similar to those reported in this paper, with no differences in CEC between treatments, and with the highest values of OM and WS-macroaggregates under CC and the lowest under NT. In the subsequent 3 years of the experiment, differences in OM have increased between CC and the other two treatments, due to a further increase in OM under CC treatment, while CT and NT presented similar values to those measured in 2003. The overall increase in OM content in the top 10 cm of the soil profile under CC treatment compared to the original levels in 1998 is similar to the one reported by Moreno et al. (2006) in a 9-year experiment in agricultural soil in Andalusia under conservation agriculture in a wheat-sunflower rotation. After 9 years, these authors found that the OM content of the top 10 cm of the soil under conservation agriculture measured 2.0% compared to 0.95% at the beginning of the experiment (Moreno et al., 1997). The relative differences in WS-macroaggregates between NT and the other two treatments had increased since a previous study made in 2003 (Gómez et al., 2003). This can be interpreted as a further degradation of the physical stability of the top-soil under the NT treatment. Due to differences in the WS-macroaggregate measurement techniques between 2003 and 2007 absolute comparisons cannot be made.

5. Conclusions

The experiment results link the reduction in soil and runoff losses under CC soil management to significant improvements in key soil properties during 7 years in an intensive olive plantation on a heavy clay soil, typical of the new expansion areas of olive cultivation in southern Spain. These results firmly suggest that CC management should be a requirement for new plantations on sloping lands, given its important effects on resource conservation, and the relatively small costs with regard to the investment required by intensive plantations. Alternative soil management methods such as chemical weed control that maintains the soil bare without tillage, NT, will lead to severe sediment losses and the worsening of the water balance by increasing runoff. It is expected that, under NT, there will be a degradation of soil properties as compared to CT, but the latter management approach will also result in significant soil losses, especially during the first years of the plantation, and lower soil quality as compared to CC. In intensive plantations, where trees cover a significant fraction of the soil, as occurred near the end of our experiment (around 40%), our results suggest that under short slope lengths and low slope steepness an olive grove might be managed under CT with moderate soil and runoff losses, although our results would have to be validated at higher space and time scales. The greater degradation of soil properties under CT as compared to CC indicates that a cover crop may be the preferred management option, either alone, or combined with CT depending on the farm's circumstances.

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