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Soil management in rainfed olive orchards may result in conflicting effects on olive production and soil fertility

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Abstract

The adoption of a sustainable soil management system is essential for the steep slopes and low fertility soils still supporting rainfed olive orchards in the Mediterranean basin. The effect of the soil management on olive yield, tree nutritional status and soil fertility was studied in a rainfed olive orchard located in NE Portugal that had been managed since its earliest days as a sheep-walk. In 2001, three different soil management systems were established: Sheep-walk, in which the vegetation was managed with a flock of sheep; Tillage, where the vegetation was controlled by conventional tillage; and Glyphosate, where a glyphosate-based herbicide was applied. The soil management systems had a pronounced effect on olive yield. The accumulated olive yields between 2002 and 2011 were 187.2, 142.9 and 89.5 kg tree^{-1}, respectively in the Glyphosate, Tillage and Sheep-walk treatments. However, the effect of soil management on tree nutritional status was not so clear. On the other hand, the pools of organic carbon and N in the soil, and also the soil available N and phosphorus (P), were found to be less in the Glyphosate and Tillage treatments in comparison with the Sheep-walk. In these soils, N appeared as a much more limiting factor for crop growth than P. In rainfed orchards, the tolerance to herbaceous vegetation appears to be a determining factor in sustainability, which regulates annual crop yields and soil fertility. The higher the tolerance to herbaceous species, the lower the olive yields, but the better are the soil fertility parameters.

Additional key words: conventional tillage; cover cropping; herbicides; *Olea europaea* L.; soil fertility; tree nutritional status.

Introduction

In the last few decades the area of irrigated olive (*Olea europaea* L.) has increased markedly in the Mediterranean basin, particularly with reference to the plantations of high-density olive orchards. The orchards, traditionally managed as rainfed systems, still retain a huge economic and social relevance, particularly on the most marginal sites of poorest soils and steep terrain. Furthermore, the high water demands of agriculture and the limited water resources in the Mediterranean basin (Wriedt *et al*., 2009), as well as the restrictions imposed on water use by the Water Framework Directive (Tánago *et al*., 2012), limit the possibilities for the extension of irrigation over wider areas of olive orchards.

Under dryland conditions, good soil management is a key factor in the cropping technique due to the conflict between the need to ensure adequate olive yields in the short-term and to protect the soil to achieve the sustainability of the agro-system in the long-term. In spite of the relevant work that has been done in the last few years, each method of soil surface management has advantages and disadvantages that merit further investigation.

Excessive soil tillage, for instance, which is still widely used in the Mediterranean region, is concern. Tillage damages the roots of the trees which may represent a great loss of carbohydrates which are then required to restore them. Additionally, regular tillage encourages soil erosion and the loss of nutrients through runoff (Gómez *et al.,* 2009). Furthermore, tillage also reduces soil organic matter (Pastor, 2008; Aranda *et al*., 2011).

Herbicides can efficiently control herbaceous vegetation, but they may also damage non-target plants such as the crop itself. Diuron, simazine and terbuthylazine may be sources of indirect phytotoxicity to olive plants (Cañero *et al*., 2011). Herbicides may also contaminate surface and ground waters (Celis *et al*., 2007). Residual

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herbicides, which keep the soil bare all year round, are an even worse strategy than tillage in controlling soil erosion (Martínez *et al*., 2006).

Cover cropping is currently the most effective practice for soil protection and maintaining the sustainability of the cropping system, as it can reduce soil erosion (Martínez *et al*., 2006; Pastor, 2008; Gómez *et al*., 2009) and increase soil organic matter and improve many other physical, chemical and biological properties of the soil compared with frequent tillage or non-covered treatments (Castro *et al.,* 2008; Moreno *et al*., 2009; Ramos *et al*., 2010, 2011). Cover crops, however, compete for resources with the trees, which can lead to a reduction in crop productivity (Hornig & Bünemann, 1993; Lipecki & Berbeç, 1997; Silvestri *et al*., 1999; Gucci *et al*., 2012). Few studies have compared grazed with ungrazed plots in perennial tree crops. Ramos *et al.* (2011) found that grazed plots had higher water content in the soil, and increased the levels of arysulphatase, β-glucosidase and phosphatase activity which was attributed to the reduction of evapotranspiration and to the stimulation of root activity by means of plant defoliation.

The objective of the research reported in this study was to evaluate the effect of different soil management treatments on olive yields, nutrient removal at harvest, nutritional status of trees and soil fertility parameters. The study was carried out in a rainfed olive orchard, subjected to three different soil management systems since 2001. Special attention was given to soil nitrogen (N) and phosphorus (P) availability, two macronutrients closely related to the sustainability of the agro-systems and whose costs are expected to increase in the near future. Nitrogen because of the high energy cost associated with its fixation by the Haber-Bosch process (Smil, 2001) and its connection with the price of crude oil and phosphorus because it is derived from phosphate rock, a finite resource whose supply will become limiting within the century (Gilbert, 2009).

Material and methods

Site characterization and experimental design

The olive orchard where this experiment took place is located in Bragança (41° 48’ N; 6° 44’ W), NE Portugal. The region benefits from a Mediterranean climate with some Atlantic influence. Average annual precipitation and temperature are 741 mm and 11.9°C, respectively. The orchard is planted in a eutric Regosol (FAO, 2006) with a sandy loam texture (12.8% clay, 32.6% silt, 54.6% sand). In 2001, when the trial started, the soil organic carbon (C) was 5.8 g kg^{-1}, pH (soil water, 1:2.5) 6.0 and extractable P and potassium (K) (Egner-Riehm) 24 and 67 mg kg^{-1}, respectively. A flock of 90-100 sheep and goats, varying yearly in number between the two species, graze an area of 12 ha. This represents an annual stocking rate close to 1.2 livestock units per hectare. An area of 5 ha of meadow was not grazed from April to June to produce a cut of hay. The remaining area, including the olive orchard, was kept under pasture all year round. The orchard is ~ 50 years old of cv. Cobrançosa and is established at a planting density of 7 m × 7 m.

In 2001, starting from natural vegetation managed as a grazed pasture, three ground-cover treatments were established: Sheep-walk, where the sward continued to be managed with a flock of sheep and goats; Tillage, consisting of two tillage passes per year in spring using a cultivator Galucho, model E-9”; and Glyphosate, a non-selective glyphosate-based herbicide (360 g L^{-1} of active ingredient; 4 L of herbicide ha^{-1}) applied once a year in April. A group of ten trees of similar canopy size were labelled in each treatment. Since the trial was established the orchard has been fertilized with 1.5 kg tree^{-1} yr^{-1} of a compound 10:10:10 (10% N, P_2O_5; K_2O) fertilizer and 7.7 g B tree^{-1} as borax. The orchard was pruned manually every three years in March 2003, 2006 and 2009.

Crop harvest and nutrient concentration in plant tissues

The trees were harvested every year in the autumn. The olive yields were weighed separately per labelled tree. The harvest, performed in the past by using wooden sticks, has been carried out in 2010 and 2011 by using a trunk-shaker machine to pull the fruits down onto sheets on the floor to recover them.

In the harvest of December 2011, a sample of 50 fruits per tree was collected and analysed for nutrient concentration. The fruit samples were separated into pulp and pit. The pulp was analysed in the green since the fat of the fruit does not allow them to be ground. The water content of the fruit samples was determined thereafter to express the results on a dry matter (DM) basis. The samples were oven-dried at 70°C to a constant weight. The pits were firstly dried and ground and then analysed. Tissue analysis was performed by Kjeldahl (N), colorimetry (B and P), flame emission spectrometry (potassium) and atomic absorption spectrophotometry (calcium, magnesium, copper, iron, zinc and manganese) methods (Walinga *et al*., 1989).

The tree plant nutritional status was assessed by plant analysis. Four leaf samples per plot were collected according to standard procedures (Freeman *et al*., 2005; LQARS, 2006) in July 2010 and 2011 and January 2011 and 2012. The leaves were oven-dried at 70°C and ground. Leaf nutrient concentrations of the most important essential plant nutrients were determined using the analytical procedures above described.

Soil fertility assessment

Soil samples were collected to assess nutrient bioavailability through chemical and biological tests. The soil was sampled at two different places in the orchard: beneath tree crop canopies and between the rows. Twenty subsamples were randomly collected to constitute a composite soil sample for each treatment and place. Four replications were prepared after mixing all the multipoint subsamples of each treatment and place. The soil was oven-dried at 40°C after being placed on trays in thin layers and thereafter sieved through a 2 mm mesh.

The analysis performed on soil samples were organic C (Walkley-Black), Kjeldahl N, pH_{H2O} (soil/water, 1:2.5), base saturation (Ca, Mg, K and Na), exchangeable acidity and cation-exchange capacity (ISRIC, 2002) and extractable P and K (Egner-Riehm) (Balbino, 1968).

A pot experiment was used as a biological assay to assess soil available N and P. The experimental design included two factors: the origin of the soil samples; and the external supply of nutrients. This second factor included three fertilizer treatments: a complete nutrient solution (control); a nutrient solution minus P; and a nutrient solution minus N. The trial included four replications (4 pots). The nutrient solutions were prepared according to Hoagland & Arnon (1950).

The pot experiment was arranged to measure the initial flush of mineralization, due to the stimulus on microbial activity caused by the pre-treatments of the soil samples (drying, meshing, re-wetting, etc.). To achieve this first objective, a short growing cycle species (turnip, *Brassica rapa*) was grown. After the cut of turnip, a second plant species was sown to measure the soil nutrient availability during the medium-term. Italian ryegrass (*Lolium multiflorum*) was selected for this step, having been managed under sequential cuts until the crop growth had stopped due to the depletion of nutrients in the soil. The biomass collected was oven-dried at 70°C and ground. Tissue P and N concentrations were determined through the laboratorial methods previously described for olive fruit samples.

Statistical analysis

Data analysis was carried out using JMP software. A completely randomized design with a single factor (soil management) was used to compare the population means (Ott & Longnecker, 2001) regarding olive yields, fruit and leaf nutrient concentrations and soil properties. We assume that there is little variability associated with position in the experiment (soil fertility, trees, etc.). The pot experiment was laid out as a completely randomized design with two factors (origin of soil samples and external nutrient supply) (Ott & Longnecker, 2001). After ANOVA examination, the means with significant differences ($p < 0.05$) were separated by the Tukey HSD test ($\alpha = 0.05$).

Results

The plot managed under the application of glyphosate produced the higher accumulated olive yields during the 2001-2011 period (Fig. 1). The lowest accu-

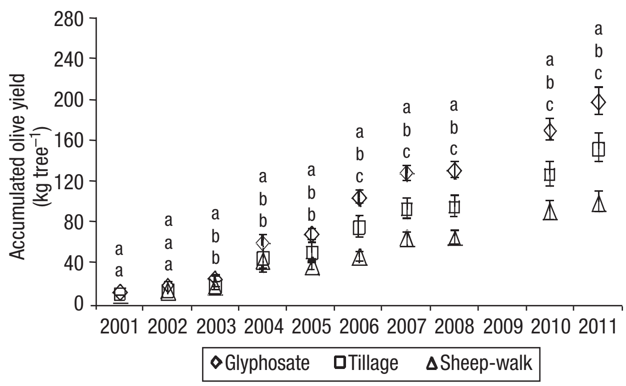

Figure 1. Accumulated olive yields from 2001 to 2011 in the plots subjected to Glyphosate, Tillage and Sheep-walk treatments. Vertical bars represent the standard deviations. Letters a, b and c are the result of the mean separation by the Tukey-HSD test ($\alpha < 0.05$) following the order Glyphosate, Tillage and Sheep-walk from top to bottom.

Table 1. Nutrient concentration in the fruit (pulp and pit) in the harvest of 2011

Treatment		Nitrogen (g kg^{-1})	Phosporus (g kg^{-1})	Potassium (g kg^{-1})	Calcium (g kg^{-1})	Magnesium (g kg^{-1})	Boron (mg kg^{-1})
Sheep-walk	Pulp	$4.46^{A\#}$	1.26^{A}	8.98^{AB}	2.26^{A}	0.84^{A}	29.11^{B}
	Pit	3.40^{a}	0.64^{a}	1.27^{a}	1.33^{a}	0.60^{a}	21.64^{a}
Tillage	Pulp	4.55^{A}	1.33^{A}	7.96^{B}	2.86^{A}	0.89^{A}	45.50^{A}
	Pit	3.57^{a}	0.76^{a}	0.97^{a}	1.70^{a}	0.62^{a}	27.08^{a}
Glyphosate	Pulp	4.47^{A}	1.32^{A}	9.80^{A}	3.02^{A}	0.93^{A}	38.12^{AB}
	Pit	3.55^{a}	0.68^{a}	1.06^{a}	1.40^{a}	0.51^{a}	26.64^{a}

\# Means followed by the same letter in columns, separately for pulp (uppercase) and pit (lowercase), are not different by Tukey HSD test ($\alpha = 0.05$).

mulated crops were recorded in the Sheep-walk treatment. The accumulated olive yields registered significant differences ($\alpha < 0.05$) from 2003 to 2011 harvests. Comparing the results of the different treatments annually, statistical differences were observed from 2002 to 2011. In all the years, the higher yields were recorded in the Glyphosate treatment and the lower values in the Sheep-walk treatment. In the year zero (2001), when the trees were tagged and before the effect of the ground-cover treatments had been manifested, the mean olive yields were not statistically different. In ten years of records, after the establishment of the ground-cover treatments (2002-2011), the sums of the crops were 187.2, 142.9 and 89.5 kg tree^{-1}, respectively in the Glyphosate, Tillage and Sheep-walk treatments.

The nutrient concentrations in the olive fruits were not statistically different among the soil management treatments for almost all the nutrients and fruit parts (Table 1). Consequently, the nutrients removed in the fruits in the 2011 harvest followed the trend observed in the olive yields. The nutrients removed in the fruits in the 2011 harvest in the Glyphosate, Tillage and Sheep-walk treatments were respectively 61.8, 54.8 and 18.3 g N, 15.6, 13.8 and 4.6 g P, 80.8, 71.7 and 24.0 g K, 32.0, 28.4 and 9.5 g Ca, 11.5, 10.2 and 3.4 g Mg and 484.1, 429.8 and 143.8 mg B. If we use nutrient concentration in the fruits in the 2011 harvest to estimate the nutrients removed in the accumulated olive yields, the values of the Glyphosate treatment represent more than twice the amount of nutrients removed in the Sheep-walk treatment.

Two years and four dates of leaf sampling did not explain much about the effect of soil management treatments on the nutritional status of trees. The concentration of nutrients in the leaves was almost the same between treatments (Table 2). Statistical differences observed in a single sampling date did not maintain the consistency in the other dates. The N concentration in the leaves might be the only exception. For two consecutive sampling dates (July 2010 and February 2011), the N concentration in the leaves of the Tillage treatment was consistently lower than that in the other treatments. In July 2010 the means presented statistical differences.

Soil organic C reached the lower values in the samples collected between rows in the Glyphosate treatment in comparison to all the other places and treatments (Table 3). The highest values, in turn, were recorded beneath the trees in the Sheep-walk treatment. Total soil N follows a similar pattern as soil organic C. Soil P and K levels were higher beneath the trees canopy in comparison to the space between rows, as a result of the regular nutrient application as fertilizer beneath the trees. Different values of Ca^{++}, Mg^{++} and cation exchange capacity were also observed, but the results might be due to a natural gradient between plots related to the parent material of the soil and not due to the effect of the soil surface management treatments.

The soil samples from beneath the trees produced higher turnip mean DM yields than the soil collected between the rows. In the Sheep-walk treatment the difference was even statistically significant (Table 4). The turnip grown in the soil from the Glyphosate treatment produced the lowest DM values. No significant differences were found in tissue N concentration of turnip grown in the soil of the different ground-cover treatments. In contrast, tissue P concentrations were particularly high for the Sheep-walk in comparison to the other treatments. The N recovery in turnip plants was mainly influenced by the DM yield while P recovery was primary determined by tissue P concentration. The N externally supplied to the soil markedly affected DM yield, tissue nutrient concentration and nutrient recovery by turnip (Table 4). When no supple-

Table 2. Leaf nutrient concentrations for four sampling dates from July 2010 to January 2012

	Nitrogen (g kg^{-1})	Phosphorus (g kg^{-1})	Potassium (g kg^{-1})	Calcium (g kg^{-1})	Magnesium (g kg^{-1})	Boron (mg kg^{-1})
22 Jul 2010						
Sheep-walk	18.71$^{ab\#}$	1.31^{a}	9.68^{a}	7.74^{a}	1.46^{a}	28.44^{b}
Tillage	17.50^{b}	1.27^{a}	9.50^{a}	7.95^{a}	1.46^{a}	31.68^{ab}
Glyphosate	18.84^{a}	1.32^{a}	10.82^{a}	7.11^{a}	1.45^{a}	32.28^{a}
3 Feb 2011						
Sheep-walk	17.64^{a}	1.34^{a}	5.84^{a}	10.20^{a}	1.58^{a}	17.44^{a}
Tillage	16.78^{a}	1.22^{a}	5.85^{a}	11.13^{a}	1.69^{a}	17.31^{a}
Glyphosate	17.71^{a}	1.28^{a}	6.44^{a}	10.68^{a}	1.61^{a}	16.55^{a}
27 Jul 2011						
Sheep-walk	15.69^{a}	1.10^{a}	9.24^{a}	5.76^{a}	1.17^{a}	21.33^{a}
Tillage	16.17^{a}	1.22^{a}	10.09^{a}	5.94^{a}	1.14^{a}	24.70^{a}
Glyphosate	16.06^{a}	1.09^{a}	9.78^{a}	5.40^{a}	1.13^{a}	23.59^{a}
11 Jan 2012						
Sheep-walk	16.44^{a}	1.35^{a}	5.94^{a}	8.67^{a}	1.34^{a}	13.91^{a}
Tillage	16.04^{a}	1.25^{ab}	5.99^{a}	8.85^{a}	1.41^{a}	13.91^{a}
Glyphosate	16.50^{a}	1.22^{b}	5.96^{a}	8.38^{a}	1.31^{a}	14.83^{a}

[#] Means followed by the same letter in columns, and for each sampling date, are not different by Tukey HSD test ($\alpha = 0.05$).

mental N was added, DM yield was 1.84 g pot^{-1}, a value significantly lower than that found in control (4.95 g pot^{-1}). In the no-N treatment, tissue N concentration and N recovery were also lower in comparison with the values recovered in the control treatment. The absence of N application also influenced P recovery, due to the reduction induced in DM yield. When no-P was added, no significant reduction in DM yield was observed. The absence of P application, however, significantly reduced the P concentration in plant tissues which significantly affected P recovery by turnip.

As observed in turnip, the dry matter yield of ryegrass was lower for the Glyphosate treatment (Table 5). The Sheep-walk treatment was associated with high N and P recoveries while the Glyphosate treatment was associated with low values. The positive effect on DM yield of the soil samples collected beneath the canopies was not observed in the growing season of ryegrass.

Table 3. Selected soil properties as a function of soil management treatment and proximity to the trunk of the trees

Soil management	Organic C (g kg^{-1})	N Kjeldahl (g kg^{-1})	P_2O_5 (mg kg^{-1})	K_2O (mg kg^{-1})	pH (H_2O)	Ca^{++} (cmolc kg^{-1})	Mg^{++} (cmolc kg^{-1})	K^{+} (cmolc kg^{-1})	Na^{+} (cmolc kg^{-1})	EA[1] (cmolc kg^{-1})	CEC[2] (cmolc kg^{-1})
Sheep-walk											
Between rows	14.8$^{ab\#}$	1.39^{ab}	74^{d}	83^{d}	5.8^{ab}	13.21^{a}	2.46^{a}	0.41^{a}	0.40^{a}	0.30^{a}	16.79^{a}
Beneath trees	16.4^{a}	1.61^{a}	155^{ab}	108^{cd}	6.1^{a}	12.31^{a}	2.18^{a}	0.43^{a}	0.44^{a}	0.30^{a}	15.66^{a}
Tillage											
Between rows	14.0^{b}	1.27^{b}	108^{cd}	119^{bc}	5.9^{ab}	8.59^{bc}	1.34^{b}	0.46^{a}	0.35^{c}	0.20^{b}	10.94^{bc}
Beneath trees	14.6^{ab}	1.37^{ab}	131^{bc}	131^{bc}	6.0^{a}	9.80^{b}	1.65^{b}	0.45^{a}	0.41^{a}	0.20^{b}	12.51^{b}
Glyphosate											
Between rows	13.8^{b}	1.29^{b}	81^{d}	146^{b}	5.4^{c}	7.44^{c}	1.26^{b}	0.43^{a}	0.36^{bc}	0.20^{b}	9.69^{c}
Beneath trees	14.3^{ab}	1.19^{b}	178^{a}	185^{a}	5.6^{bc}	8.57^{bc}	1.48^{b}	0.52^{a}	0.40^{ab}	0.20^{b}	11.17^{bc}

[1] EA: exchangeable acidity. [2] CEC: cation exchange capacity. [#] Means followed by the same letter in columns are not different by Tukey HSD test ($\alpha = 0.05$).

Table 4. Soil N and P bioavailability assessed by growing turnip in a pot experiment as a function of soil management treatment and N and P supply

	DM yield (g pot^{-1})	Plant N conc. (g kg^{-1})	Plant P conc. (g kg^{-1})	N recovery (mg pot^{-1})	P recovery (mg pot^{-1})
Soil management (SM)					
Sheep-walk					
Between rows	3.49[b#]	18.06[a]	3.20[a]	63.03[b]	11.17[b]
Beneath trees	4.59[a]	18.16[a]	3.33[a]	83.35[a]	15.28[a]
Tillage					
Between rows	3.89[b]	18.14[a]	2.35[b]	70.56[ab]	9.14[c]
Beneath trees	3.92[ab]	18.95[a]	1.82[c]	74.28[ab]	7.10[cd]
Glyphosate					
Between rows	3.74[b]	19.32[a]	1.81[c]	72.66[ab]	6.77[cd]
Beneath trees	3.77[b]	18.81[a]	1.73[c]	70.91[ab]	6.52[d]
Nutrient supply (NS)					
+P – N	1.84[b]	13.51[b]	3.01[a]	24.86[b]	5.54[c]
+N – P	4.92[a]	21.42[a]	2.31[b]	105.39[a]	11.37[b]
+N + P (control)	4.95[a]	20.83[a]	2.80[a]	103.11[a]	13.86[a]
Prob > F					
SM	0.001	0.072	0.000	0.000	0.000
NS	0.000	0.000	0.000	0.000	0.000
SM × NS	0.304	0.066	0.095	0.000	0.270

[#] Means followed by the same letter in columns, separately for soil management and nutrient supply, are not different by Tukey HSD test ($\alpha = 0.05$).

The effect of nutrient supply on the soil samples affected DM yields, tissue nutrient concentration and nutrient recovery of ryegrass in a similar manner as observed in turnip. The starvation of N significantly decreased DM yield, tissue N concentration and N and P recoveries. The lack of P did not cause a decrease in DM yield but decreased tissue P concentration and recovery.

Discussion

The soil surface management systems had a pronounced effect on olive yield. The trees of the Tillage plot produced less than the trees of the Glyphosate plot. The poor performance usually found when the olive orchards are managed by conventional tillage has been attributed to the damage caused to the root system making water and nutrient uptake difficult (Tisdall, 1989; Anderson *et al.*, 1992) and to the subsequent carbohydrate consumption required to restore it (Rodrigues & Cabanas, 2009). The Sheep-walk treatment produced the lowest olive yields. Cover cropping usually reduces crop production (Lipecki & Berbeç, 1997; Silvestri *et al.*, 1999; Gucci *et al.*, 2012), presumably due to the competition for water and nutrients between the herbaceous species and the trees. In rainfed orchards the competition for water might be more important considering the long summer period of the Mediterranean region (Rodrigues & Cabanas, 2009; Rodrigues *et al.*, 2011a). However, a shortfall in production has also been recorded in irrigated orchards managed under cover cropping (Hornig & Bünemann, 1993; Lipecki & Berbeç, 1997; Gucci *et al.*, 2012), which may mean that the competition for nutrients could also be important. In a vineyard with a cover crop introduced in the interrows, Celette *et al.* (2008) found that the root system of the grapevine was forced to explore deeper layers of the soil due to the presence of the root system of the cover crop that had been established first during the winter resting period of the grapevine. Thus, a cover crop established before the spring growth of trees can exert a strong competitive effect for available nutrients in the topsoil. However, the problem could not be the cover crop *per se* but how we manage it.

Table 5. Soil N and P bioavailability assessed by growing ryegrass in a pot experiment as a function of soil management treatment and N and P supply

	DM yield ($g\ pot^{-1}$)	Plant N conc. ($g\ kg^{-1}$)	Plant P conc. ($g\ kg^{-1}$)	N recovery ($mg\ pot^{-1}$)	P recovery ($mg\ pot^{-1}$)
Soil management (SM)					
Sheep-walk					
Between rows	2.75[bc#]	31.79[a]	2.82[a]	87.42[abc]	7.76[a]
Beneath trees	2.81[ab]	33.28[a]	2.58[a]	93.51[a]	7.25[a]
Tillage					
Between rows	3.05[a]	31.25[a]	2.62[a]	95.31[a]	7.99[a]
Beneath trees	2.70[bc]	33.02[a]	2.39[a]	89.15[ab]	6.18[b]
Glyphosate					
Between rows	2.33[d]	34.13[a]	2.55[a]	79.52[c]	5.94[b]
Beneath trees	2.49[cd]	32.83[a]	2.96[a]	81.75[bc]	7.37[a]
Nutrient supply (NS)					
+P – N	1.79[b]	27.15[b]	2.87[a]	48.60[c]	5.14[c]
+N – P	3.10[a]	34.87[a]	2.02[b]	108.10[b]	6.26[b]
+N + P (control)	3.18[a]	36.30[a]	3.07[a]	115.43[a]	9.76[a]
Prob > F					
SM	0.000	0.053	0.105	0.000	0.000
NS	0.000	0.000	0.000	0.000	0.000
SM × NS	0.072	0.044	0.065	0.085	0.000

[#] Means followed by the same letter in columns, separately for soil management and nutrient supply, are not different by Tukey HSD test ($\alpha = 0.05$).

Ramos *et al.* (2011) recorded higher water content in the soil in a plot managed by fencing a flock of 130 sheep in 0.4 ha when the grass was removed early on by grazing, in comparison with other ground-cover treatments.

The analysis of the nutritional status of trees showed that the ground-cover systems did not have a marked effect on leaf nutrient concentration. A complex set of interactions may explain the result, such as: the most productive trees might have taken up more nutrients, but the associated increase in nutrient removal in the fruits reduced the fluctuation in the leaf nutrient concentration; the higher soil nutrient availability may have produced a stimulus in vegetative tree crop growth, hence producing a dilution effect on the nutrient concentration in the tissues, an aspect widely referenced in the literature (Smith, 1962; Jarrell & Beverly, 1981), and the nutrient concentration in the leaves remained above the threshold limit, as defined in the literature (Freeman *et al.*, 2005; Fernández-Escobar, 2008), having low sensitivity to the small fluctuations in soil available nutrients. However, there was some evidence that the trees of the tillage plot showed lower N concentrations in leaves than that of the other treatments for two consecutive sampling dates, July 2010 and February 2011. The first pass of soil tillage occurs late in the winter or early spring, shortly after the application of fertilizers. The passage of the cultivator incorporates the fertilizer, kills the weeds but also destroys the root system of the trees developing in the topsoil, impairing water and nutrient uptake at an important phase of tree crop growth and development. Thus, tillage restricting the opportunity for root uptake may have reduced the nutrient use efficiency. The negative effect of tillage on N uptake would be more pronounced than in the other soil management systems due to the transient nature of this nutrient in the soil, resulting in lower leaf N concentrations at some sampling dates.

The chemical soil fertility evaluation revealed higher organic C and total N in the soil in the Sheep-walk treatment than those in the Tillage and Glyphosate treatments. The result is attributed to the deficient control of the herbaceous vegetation in spring in the Sheep-walk treatment. Over the years, the balance established between the C and N sequestered in the soil and that which was mineralized has been more positive, resulting in a progressive increase in the pools of organic C and N in the soil in the Sheep-walk treatment. Previous studies have already shown that cover cropping, compared to tillage or non-covered treatments, leads to an improvement in soil quality by increasing the organic matter content and enhancing soil biological activity (Castro *et al*., 2008; Moreno *et al*., 2009; Ramos *et al*., 2010, 2011; Aranda *et al*., 2011; Gucci *et al*., 2012). This makes cover cropping the best option for soil management in rainfed orchards (Moreno *et al*., 2009; Ramos *et al.,* 2011). The use of cover crops also helps mitigate the intensity of water erosion (Martínez *et al*., 2006; Gómez *et al.,* 2008, 2009) an important factor in the sustainability of the agrosystems in the Mediterranean basin.

In the pot experiment, the soil samples from the Glyphosate plot produced less biomass in both the turnip and ryegrass crops, comparative to the Tillage and Sheep-walk treatments. The main reason would be the lower organic matter content in the plot managed with glyphosate. Since tissue N concentrations were not different among the soil management treatments, N recoveries in plant biomass varied according to the DM yields. In the case of P, tissue P concentrations were significantly higher in the turnip plants growing in the soil samples from the Sheep-walk treatment, although no effect on DM yields was observed. Probably the shortage of P was not high enough to be a limiting factor for crop growth. The addition of external N strongly increased DM yield, while the effect of P addition was modest. N appears as a major limiting factor for crop growth in these soils. The result is corroborated by others reported by Rodrigues *et al.* (2011b) where the olive yields decreased over a short period of time of three years if N was not applied as a fertilizer. The pot experiment also seems to indicate the higher olive yields that have been recorded in the Glyphosate treatment and the reduced tolerance to herbaceous vegetation as having a negative impact on the potentially available soil N and P pools, which may adversely affect the sustainability of the production system.

As conclusions, the higher olive yields found in the Glyphosate treatment seem to be justifiable by the efficient control of the herbaceous vegetation early in spring, which would reduce the competition for water and nutrients. In the Tillage plot, the nutrient use efficiency from the soil and applied fertilizers was probably reduced by the damage caused to the root system in the spring by the tillage implements. In the case of the Sheep-walk in this particular experiment, the animals achieved a very poor control of vegetation in the spring, when a boom of biomass production occurs, surpassing their food needs. This period coincides with flower bud development and flowering, the most sensitive phase in olive to water and nutrient stress. Thus, the soil surface management system less tolerant to the herbaceous vegetation gave higher olive yields, while the system which was more tolerant to the herbaceous vegetation showed better soil quality parameters.

In rainfed orchards the best solution may be the establishment of a permanent ground-cover crop, but efficiently controlled in the spring, thus ensuring the protection of the soil without excessive competition for water and nutrients with the olive trees. The present study was, however, only focused on the tree crop performance and some soil quality factors. A decision at farm level should consider other aspects, such as the energy use and the cost and income from other agricultural activities as is the extensive sheep and goat grazing in the case of the farm where this experiment was carried out.

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