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Grazing, tilling and canopy effects on carbon dioxide fluxes in a Spanish dehesa

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Abstract There is increasing interest in carbon sequestering capacity of agroforestry systems especially in relation to climate change. Appropriate implementation of silvopastoral practices in dehesa systems may contribute to their sustainability; improve soil carbon (C) and nitrogen (N) storage capacity while reducing the carbon dioxide (CO_2) flux from the soil to the atmosphere. The response of soil respiration (R_s) to grazing and tilling practices and trees canopy influence were studied in a dehesa ecosystem in the center of Spain from July 2008 to February 2010. Four different treatments were established: non grazed-non tilled; non grazed-tilled; grazed-non tilled and grazed and tilled. In all the treatments R_s, soil temperature (T_s), soil moisture (M_s), soil C and N stocks were measured. Grazing reduced R_s by 12 % across all experiment. Increments of 3 Mg/ha in C stocks and 0.3 Mg/ha in N stocks in grazing soils were observed. Although, no clear tilling effect on R_s was found, a decrease of 3.5 Mg/ha in soil C stocks and 0.3 Mg/ha in N stocks was detected in tilled soils. Presence of tree canopy induced increases in R_s, soil C and N stocks; while decreases in T_s were observed, but grazing decreased the tree canopy influence on annual C losses by R_s. The M_s constrained the temperature response of R_s during the experiment, and meaningful Q_{10} values were only obtainable during the wettest time, ranging from 2.5 to 5.7. Grazing and tree canopy had a positive influence in the ability of soils to store soil C and N, while tilling had a negative effect on soil C and N store capacity in this study. Maintaining the beneficial practices and improving tillage management in this area may have important consequences in carbon sequestration capacity in this dehesa system.

Keywords Dehesa · Soil respiration · Soil C stock · Soil N stock · *Quercus ilex* · Climate change

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Introduction

Dehesa are multipurpose agrosilvopastoral systems of extensive utilisation, where native trees, mostly holm *Quercus ilex* and cork *Quercus suber* oaks, are spaced out or inserted in a continuum of grasslands or shrubland matrix (Díaz et al. 1997; Ramachandran Nair et al. 2009). As a result, dehesa systems are distinguished by a systematic combination of agricultural, pastoral and forestry uses, resulting in different vegetation structures depending on land-use (Cubera and Moreno 2007; Joffre et al. 1999). Dehesas cover about 5–6 million hectares of the Iberian peninsula (Sundseth 2009) and have influenced the landscape for many centuries in the Mediterranean basin (Eichhorn et al. 2006).

In recent years, the sustainability of dehesas has come into question with the trend towards more intensive and simplified management (Cubera and Moreno 2007; Papanastasis 2004) and the insufficient regeneration of trees (Plieninger et al. 2003; Pulido et al. 2001). Apart from producing important environmental services, trees constitute an important means of capturing and storing carbon (C) atmospheric in biomass and soils (Malhi et al. 2008). More recently, there has been increasing interests in the C sequestration capacity of agroforestry systems, especially under the afforestation and reforestation mitigating strategies under the Kyoto Protocol (IPCC 2007; Ramachandran Nair et al. 2009). Agroforestry systems are believed to have a higher potential to sequester C than either pastures or field crops (Kirby and Potvin 2007; Ramachandran Nair et al. 2009; Sanchez 2000; Sharrow and Ismail 2004). On the other hand, arid and semiarid sites have lower C sequestration potential than more fertile and humid sites (Jose 2009; Ramachandran Nair et al. 2009).

The use of appropriate silvopastoral practices in dehesa systems may contribute to their sustainability, improve soil quality and productivity, and reduce the soil carbon dioxide (CO_2) flux from the soil to the atmosphere. Tillage is commonly used in dehesas for various periodical crops, to control shrub encroachment, favour the grass layer, and obtain complementary fodder for grazing animals (useful for dry and cold seasons) (Cubera and Moreno 2007; Moreno and Obrador 2007). In Spain it is common to apply a systematic periodical tillage of mouldboard ploughing in dehesas to prevent potential compaction problems and encourage seedling emergence and crop performance (López-Garrido et al. 2011). Different types of livestock are usually employed in dehesas to make best use of the varied resources; grazing of cattle, sheep, Iberian pigs, etc. can influence plant community structure, soil properties, and the distribution and cycling of nutrients within the plant-soil system (Schuman et al. 1999). Previous studies in Mediterranean agroecosystems have shown that tillage increases soil respiration (R_s) in the short-term (Álvaro-Fuentes et al. 2007; López-Garrido et al. 2009; Morell et al. 2010), caused by the alteration of microclimate and soil organic matter decomposition after tillage. Tillage promotes aggregate disruption, exposes protected organic matter to decomposition (La Scala et al. 2008), and contributes to the mixing of plant residues with soil that in turn increase soil microbial activity, causing an increase in R_s due to release of gases entrapped in soil pores from previous microbial activity related the increase in R_s after tillage (*burst* effect) (Reicosky et al. 1997). Small differences in R_s between tillage and no-tillage treatments in the first weeks after tillage have been documented (Ball et al. 1999; Reicosky and Lindstrom 1993), but, less information is available on mid-and long-term effects of tillage practice on R_s. Moreover, no clear relationship between grazing and R_s has been observed in semiarid grassland ecosystem (Milchunas and Lauenroth 1993; Reeder and Schuman 2002), or a decline in R_s with grazing has been observed (Bremer et al. 1998; Cao et al. 2004; Raiesi and Asadi 2006). Some authors have reported variations in R_s in response to rates of nitrogen input from cattle excreta (Jones et al. 2006) and reductions in root respiration rate and organic matter decomposition alteration due to grazing activities (Bremer et al. 1998; Detling et al. 1979; LeCain et al. 2002). However, the complexity of the mechanism involved in herbivore effects on soil processes makes predicting the direction and magnitude of these effects often very difficult (Bardgett et al. 1998; Mazancourt et al. 1998; Stark et al. 2000). Consequently, the effects of grazing management on the biogeochemical processes that control the exchange of C between the soil and atmosphere are not fully understood in semiarid grassland ecosystems, (Reeder and Schuman 2002).

Together, the type, frequency, intensity and timing of these management practices (tillage, grazing), may, in addition to environmental controls, modify the R_s dynamics in dehesa systems. Understanding the response of R_s to management is crucial to our ability to predict the impact of current and management regimes on regional C exchange; and to establish strategies to help mitigate greenhouse gases emissions.

The objectives of this study were to (1) quantify the effects of pasture and tillage practices on R_s, (2) determine the influence of the management practices

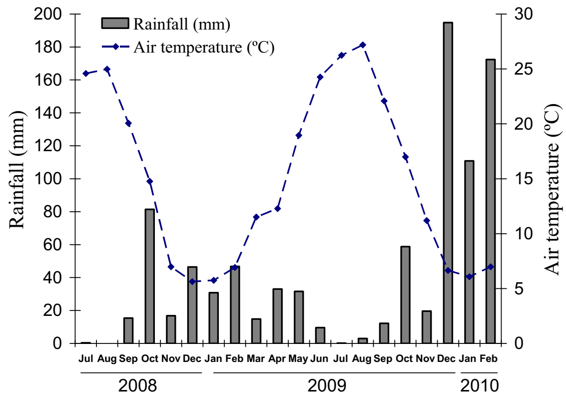

Fig. 1 Monthly temperatures and accumulated rainfall from meteorological station in *Dehesón del Encinar* during the experiment (2008–2010)

on soil C and N stocks and the response of R_s to soil microclimate, and (3) determine the influence of tree canopy (*Quercus ilex*) on R_s, soil C and N stock in a dehesa ecosystems situated in the center of Spain (Toledo).

Materials and methods

Study area

The experiment was conducted from July 2008 to February 2010 in a dehesa ecosystem, *Deheson del Encinar* in the center of Spain (Oropesa, Toledo) (39°59′N, 5°8′W). The site was located at an approximate altitude of 350 m asl, occupied ~714 ha on moderate slopes.

The climate was Mediterranean seasonally wet oceanic with a mean annual precipitation of 572 mm and a mean annual temperature of 15.3 °C (Rivas-Martínez and Rivas-Saenz 2010). Meteorological data during the experiment were obtained from the meteorological station installed in the *Deheson del Encinar* (Fig. 1). The vegetation in the experimental area was composed of herbaceous stratum and a tree canopy stratum of evergreen oak *Quercus ilex* L. subsp. *ballota* (Desf.) Samp. Mean tree density was around 32 trees/ha. Trees had a mean crown radius of about 4.3 ± 1 m, height 8.3 ± 2 m and diameter 46.8 ± 19.1 cm. The grass layer vegetation was comprised of annual subnitrophilous pastures of the *Stellarietea mediae* and *Sisymbrietalia officinalis* (López-Carrasco et al. 2012). The majority of pasture growth in these annual communities occurs in April–May (around 70 % of the annual yield, according to (Olea et al. 1990–1991)), and herbaceous plants generally dry between mid June and October.

Soils were classified as Haplic luvisol and Haplic cambisol (IUSS 2007; Simón et al. 2012). Soil characteristics of this dehesa have been described by Simón et al. (2012), and are acidic, sandy and poor in nutrient and organic matter content (Gea-Izquierdo et al. 2009). Most common activities in *Deheson del Encinar* are research, livestock grazing with native and artificial intercropping pasture and more marginal activities such as firewood, cork production and hunting. In the farm areas used in the study the management system was grazing by sheep (2–3 Talaverana heads/ha) from mid April to June and grazing by cattle (6–8 Avileña heads/ha) during summer months.

Experimental layout

Two grazed and two non-grazed areas of around 1.5 ha each were established in the dehesa. The distances between the four experimental areas were from 600 m to 3 km. Within each area, eight trees of *Quercus ilex* were randomly selected (at about fifty meters of distance between them), four of which trees were tilled in April 2008 using conventional deep (20–25 cm) mouldboard ploughing in a 30 m^2 area approximately around each trunk; the other four trees remained untilled in each area (Fig. 2). Soils in the dehesa had not been tilled since 1987. Thus a total of four different treatments were obtained: Non grazed-non tilled (NGNT); non grazed-tilled (NGT); grazed-non tilled (GNT) and grazed-tilled (GT) with two replicates per treatment (consisting of four trees per treatment rep) (Fig. 2).

PVC collars were installed (diameter 10 cm × height 4.5 cm) in all the treatments into the soil at 2.5 cm depth to limit root severing, at least 1 week prior to investigation to the first R_s measurements to prevent an overestimation of GAS fluxes. Four collars were installed under tree canopy (UC) in the N, S, E, and W orientations in a subset of four trees in each treatment. Besides, to evaluate the effect of canopy cover, one additional collar out of the influence of canopy in open area (OA) were installed in each tree,

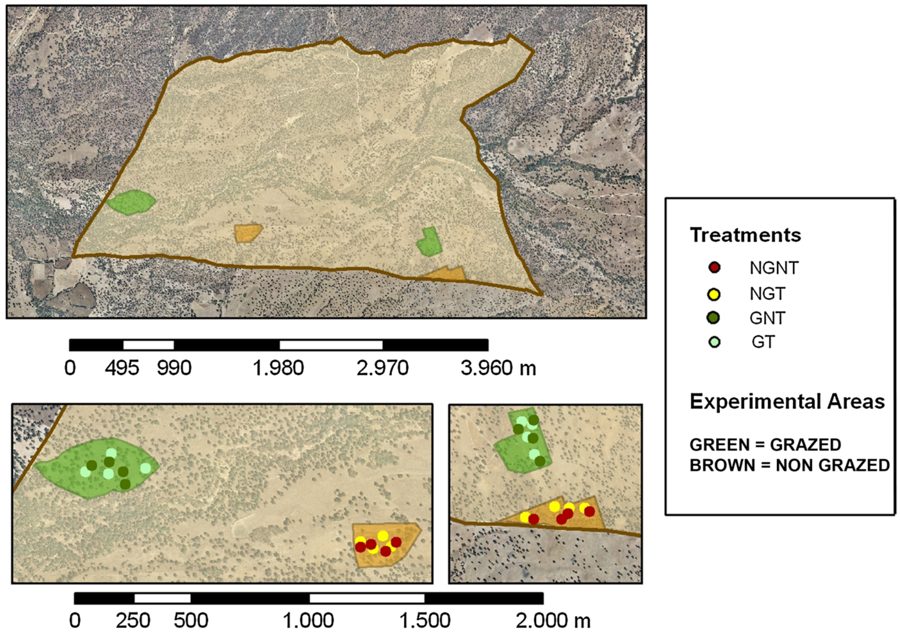

Fig. 2 Experimental design of *Dehesón del encinar* with experimental areas and location of different treatment sites: *NGNT* non grazed-non tilled, *NGT* non grazed-tilled, *GNT* grazed-non tilled, *GT* grazed-tilled

only in non tilled treatments (NGNT and GNT).The average distances between tree layer and R_s collars were about 3 m in UC and 11 m in OA. A total of 144 collars were installed during the experiment in all treatments. R_s was measured at nine different times from July 2008 to February 2010: July, August, October, November and December 2008; March, April and September in 2009 and February 2010, using a closed dynamics system LI-6400 coupled to an LI-6400-9 soil chamber (LI-COR inc., Lincoln, NE, USA). All measurements during the experiment were made between 10 am and 5 pm. Inside the collars, the emerging ground vegetation was trimmed without altering the soil surface and removed in conjunction with coarse materials before inserting the soil chamber. The measurement of R_s consisted of placing the chamber on the collar, scrubbing the CO_2 to sub-ambient levels and measuring the flux rate as it rose from 15 ppm below to 15 ppm above the atmospheric value according to LI-6400 owner manual. The R_s measurements were taken on clear days and not performed on days following a rain event to avoid an overestimation of the efflux due to CO_2 displacement from soil pores. Three measurements of R_s were made on each collar at each observation point. Coincident with the R_s measurement, T_s and volumetric M_s (at 10-cm depth) were recorded in three points around each collar with a thermocouple sensor (Omega Engineering, Stamford, CT) and time-domain reflectometry system (TRIMEGM, IMKO GmbH, Ettlingen, Germany). The annual C emission was calculated from average R_s values in each of treatments (μmol m^{-2} s^{-1}), extrapolated to a year and expressed as g C m^{-2} yr^{-1}.

Soil sampling and analysis

At the end of the experiment, two soil cores samples were taken beneath each collar used in the R_s measurements, after removal of plant debris from the surface. One of the core samples (diameter 6 cm × height 5 cm) was used to calculate soil bulk density, the other for soil C and N analysis. The samples were kept separately in plastic bags and transported on ice in a dark cooler to the laboratory. Bulk density (B_d) was calculated as mass of the oven-dry soil (110 °C for 48 h) divided by the core volume. The soil samples for C and N analysis were air dried at room temperature for 2–3 days, sieved thought a 2 mm mesh then ground and homogenized using a mortar and C and N content determined using a LECO TruSpec CHN elemental analyzer (LECO Corp., St. Joseph, USA). Soil C and N stocks (Mg ha^{-1}) were calculated based on soil C and N concentration of the fine fraction (g/kg) and soil B_d (g/cm^3) to a depth of 5 cm.

Table 1 Mean values and standard error of soil respiration (R_s µmol m^{-2} s^{-1}), soil temperature (T_s °C) and soil moisture (M_s %) across the entire experiment (2008–2010) and for the different periods in each treatment *NGNT* non grazed-non tilled, *NGT* non grazed-tilled, *GNT* grazed-non tilled, *GT* grazed-tilled

Time	Treatment	R_s	T_s	M_s
All experiment	NGNT	1.96 ± 0.08 (187)	16.63 ± 0.50 (187)	4.41 ± 0.23 (165)
	NGT	1.90 ± 0.07 (138)	12.79 ± 0.55 (138)	6.47 ± 0.47 (133)
	GNT	1.69 ± 0.06 (227)	16.43 ± 0.48 (227)	6.29 ± 0.46 (166)
	GT	1.73 ± 0.07 (177)	12.36 ± 0.43 (177)	7.65 ± 0.56 (177)
Hot, dry period	NGNT	1.66 ± 0.15 (83)	22.11 ± 0.34 (83)	3.04 ± 0.25 (69)
	NGT	0.88 ± 0.11 (23)	23.05 ± 0.73(23)	1.70 ± 0.28 (23)
	GNT	1.17 ± 0.07 (95)	23.82 ± 0.41 (95)	2.45 ± 0.25 (34)
	GT	0.90 ± 0.15 (31)	20.44 ± 0.64 (31)	1.93 ± 0.19 (31)
Cold, moist period	NGNT	2.14 ± 0.17 (37)	7.19 ± 0.23 (37)	9.39 ± 0.50 (29)
	NGT	2.24 ± 0.14 (45)	6.27 ± 0.21 (45)	13.59 ± 0.66 (40)
	GNT	2.05 ± 0.14 (40)	6.69 ± 0.22 (40)	14.05 ± 1.23 (40)
	GT	2.25 ± 0.16 (47)	6.17 ± 0.21 (47)	16.84 ± 1.32 (47)
Mid period	NGNT	2.24 ± 0.10 (67)	13.80 ± 0.36 (67)	3.69 ± 0.18 (67)
	NGT	2.02 ± 0.09 (70)	13.62 ± 0.48 (70)	3.97 ± 0.19 (70)
	GNT	2.06 ± 0.10 (92)	13.02 ± 0.25 (92)	4.33 ± 0.19 (92)
	GT	1.73 ± 0.06 (99)	12.76 ± 0.38 (99)	5.07 ± 0.21 (99)

Values in parenthesis indicate number of data points

Hot, dry period corresponds to the months of July 2008; August 2008; October 2008 and September 2009

Cold moist period corresponds to the months of December 2008 and February 2010

Mild period corresponds to the months of November 2008; March 2009 and April 2009

Statistical analysis

Data were checked for homogeneity of variances and for normal distribution using Levene and Kolmogorov–Smirnov test respectively. Two-way ANOVA was used to evaluate (1) the effects of grazing and tilling on R_s, T_s, M_s, C and N stocks in all treatments; (2) the effect of canopy on C and N stocks in non tilled treatments. A one-way ANOVA was used to test differences in R_s, T_s and M_s between NGNT and GNT in July and August 2008; and canopy influences on R_s, T_s and M_s in non tilled treatments. Post-hoc means comparisons were performed using Tukey's HSD test. A Spearman-rank correlation test was used to examine the relationship between R_s T_s and M_s for each treatment combination. Apparent Q_{10} values were determined using the model described in (Janssens and Pilegaard 2003).

Due to strong seasonality of Mediterranean ecosystems, the correlations between R_s and soil microclimate were performed across the whole data set in each treatment, and on data set from three broad climatologically periods of the dehesa, representing (1) dry months, characterized by high temperatures and low moisture ($T_s > 25$ °C, M_s 1–5 %), hereafter called "hot, dry period" corresponds to the months of July 2008; August 2008; October 2008 and September 2009; (2) cold months, characterized by low temperature and high moisture ($T_s < 7$ °C, M_s 8–28 %), hereafter called "cold, moist period" corresponds to the months of December 2008 and February 2010; and (3) warmer months, characterized by mild temperature and moisture ($T_s > 11$ °C, M_s 2–6 %), hereafter called "mild period" corresponds to the months of November 2008, March 2009 and April 2009 (Table 1). All statistical analyses were performed using the Statistica 6.0 sofware package (StatSoft. Inc., Tulsa. USA) and Sigma Plot 6.0 (SystatSoft. Inc., San Jose, USA) using a 5 % probability level for significance.

Results

Soil respiration (R_s), soil temperature (T_s) and soil moisture (M_s)

Pasture and tillage treatments

Periodic mean values of R_s (μmol m^{-2} s^{-1}) obtained during the experiment in the different treatments are shown in (Fig. 3a). The R_s (μmol m^{-2} s^{-1}) across the measurements ranged from 0.34 to 8.48 in NGNT, from 0.11 to 6.02 in NGT, from 0.30 to 5.71 in GNT and from 0.31 to 5.28 in GT.

Grazing significantly decreased R_s ($p < 0.05$) by 26 % in July 2008, 48 % in August 2008, 24 % in April 2009 and 38 % in September 2009. Tilling resulted in less consistent responses: a 20 % decrease in R_s ($p < 0.05$) in November 2008, and an increase of 32 % ($p < 0.05$) in February 2010. A significantly interaction effect between grazed and tilled treatment ($p < 0.05$) was observed in September 2009 only (Fig. 3a).

Grazing resulted in an increase in T_s values ($p < 0.05$) in July 2008, and a decrease ($p < 0.05$) in October 2008, December 2008 and April 2009. Tilling lowered T_s values ($p < 0.05$) in November and December 2008 and increased T_s values ($p = 0.1$) in February 2010 (Fig. 3b). Grazed areas showed an increase of M_s in November 2008, April 2009 and February 2010; and higher M_s values were found in tilled treatments in December 2008, March 2009 and April 2009, respectively. However, in December 2008 there was a significant interaction between grazed and tilled treatment effects on M_s with most pronounced tilling effect in the ungrazed area (Fig. 3c).

Across all data, the R_s was 12 % lower in grazed than in non grazed treatments, but no significant differences were found with tilling and there was no interaction between both treatments (grazing × tilling). Furthermore, we observed a positive effect of grazing and tilling treatments on M_s and negative effect on T_s by tilling. Estimated annual C losses through R_s associated with the different agrosilvopastoral practices were 742 g C m^{-2} yr^{-1} for NGNT, 719 g C m^{-2} yr^{-1} for NGT, 640 g C m^{-2} yr^{-1} for GNT and 655 g C m^{-2} yr^{-1} for GT.

Mean R_s rates (μmol m^{-2} s^{-1}) for each treatment across the entire experiment and for the different climatic periods selected are shown in Table 1. Lowest

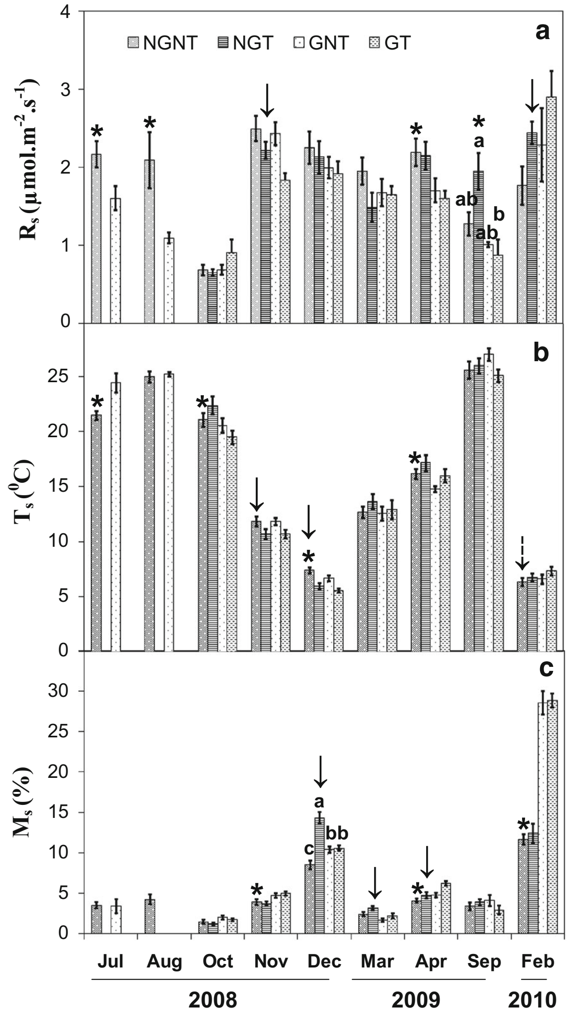

Fig. 3 Mean values and standard errors of **a** soil respiration (R_s μmol m^{-2} s^{-1}); **b** soil temperature (T_s °C); and **c** soil moisture (M_s %) during the experiment in each treatment; *NGNT* non grazed-non tilled, *NGT* non grazed-tilled, *GNT* grazed-non tilled, *GT* grazed-tilled. Where asterisks indicate significant effect ($p = 0.05$) of grazing, arrows indicate significant effect ($p = 0.05$) of tilled and discontinuous arrow indicate significant effect at $p = 0.1$ by measurement period. *Different letters* show interaction between grazing and tilled treatments

R_s values were observed in the hot and dry period (Table 1). Using the data obtained from the whole experiment, Spearman rank correlation coefficients (Table 2) showed a weak negative relationship between R_s and T_s and weak positive relationship between R_s and M_s. The correlations between R_s, T_s, and M_s were slightly stronger in the grazed than the corresponding ungrazed treatments; while the correlation with M_s was

Table 2 Spearman correlation coefficients between soil respiration (R_s), soil temperature (T_s) and soil moisture (M_s) with all data obtained during the experiment (2008–2010) and for the different periods in "*Dehesón del Encinar*" in each treatment; *NGNT* non grazed-non tilled, *NGT* non grazed-tilled, *GNT* grazed-Non tilled; *GT* grazed-tilled

Treatment	All experiment		Hot, dry period		Cold, moist period		Mild period	
	$R_s - T_s$	$R_s - M_s$	$R_s - T_s$	$R_s - M_s$	$Rs - T_s$	$R_s - M_s$	$Rs - T_s$	$R_s - M_s$
NGNT	**−0.33** (187)	**0.31** (165)	n.s	**0.51** (59)	**0.44** (37)	n.s	n.s	n.s
NGT	**−0.29** (138)	**0.41** (133)	n.s	**0.38** (23)	**0.40** (45)	n.s	n.s	n.s
GNT	**−0.43** (227)	**0.37** (166)	**0.29** (99)	n.s	**0.31** (40)	n.s	**−0.19** (92)	**0.26** (92)
GT	**−0.39** (177)	**0.45** (177)	n.s	n.s	**0.39** (47)	**0.33** (47)	n.s	n.s

Values in parenthesis indicate number of data points

All bold coefficients values show in the table are significant ($p < 0.05$)

n.s no significant values

Hot, dry period corresponds to the months of July 2008; August 2008; October 2008 and September 2009

Cold moist period corresponds to the months of December 2008 and February 2010

Mild period corresponds to the months of November 2008; March 2009 and April 2009

more strongly positive in the tilled treatments. When the data were analyzed by climatic periods, different patterns emerged and the correlation between R_s and M_s became generally less pronounced. In the hot, dry period R_s was uncorrelated with T_s in all but the GNT treatments, and only in non-grazed treatments (NGNT–NGT) was there a positive correlation between R_s and M_s. In the cold moist period, a positive correlation between R_s and T_s was detected in all treatments; whereas a positive correlation between R_s and M_s was observed only in the GT treatment. In the mild period, there was no significant correlation between R_s and soil microclimate, except in GNT where R_s was positively correlated with M_s and negatively with T_s. Therefore, the apparent Q_{10} was calculated only for the cold moist period, with Q_{10} values of 5.68 for NGNT, 2.47 for NGT, 2.88 for GNT and 4.12 for GT.

Influence of tree canopy

The periodic mean R_s values (μmol m^{-2} s^{-1}) were higher ($p < 0.05$) under tree canopy than in open areas during most of the experiment, irrespective of grazing treatment. (Figures 4a, 5a). Annual C losses through R_s were on average 33 and 18 % less in open compared to under canopy areas in the NGNT and GNT treatment, respectively. Canopy cover had an attenuating effect on T_s, which was generally lower ($p < 0.05$) under canopy compared to open locations (Figs. 4, 5b) except during the coldest months, when T_s was higher below the tree canopy. Differences in M_s were generally less pronounced, but when they occurred, higher M_s ($p < 0.05$) were generally observed in open areas (Figs. 4c, 5c).

Under the canopy no significant differences in R_s were found with orientation, although aspect significantly influenced soil microclimate, with higher T_s values and lower M_s values ($p < 0.05$) in the S compared to the N across all treatments.

Soil C and N stocks

Mean values of B_d (g/cm^3), C and N stocks (Mg/ha) and C/N ratio from this experiment are shown in Table 3. No significant differences in B_d data were found due to canopy or management treatment (Table 3). Grazing increased soil C and N stocks ($p < 0.05$) while tilling decreased these stocks ($p < 0.05$). Furthermore, there was a significant interaction ($p < 0.05$) between grazing and tilling effects on soil C and N stocks (Mg ha^{-1}) such that increases in C and N stock with grazing were most pronounced in untilled sites and diminished with tilling. Mean C and N stocks values (Mg ha^{-1}) under tree canopy were two to three times the value ($p < 0.05$) of those in open areas (Table 3).

Discussion

Grazing influences

Grazing clearly decreased R_s values in our experiment when the whole experimental data set was considered.

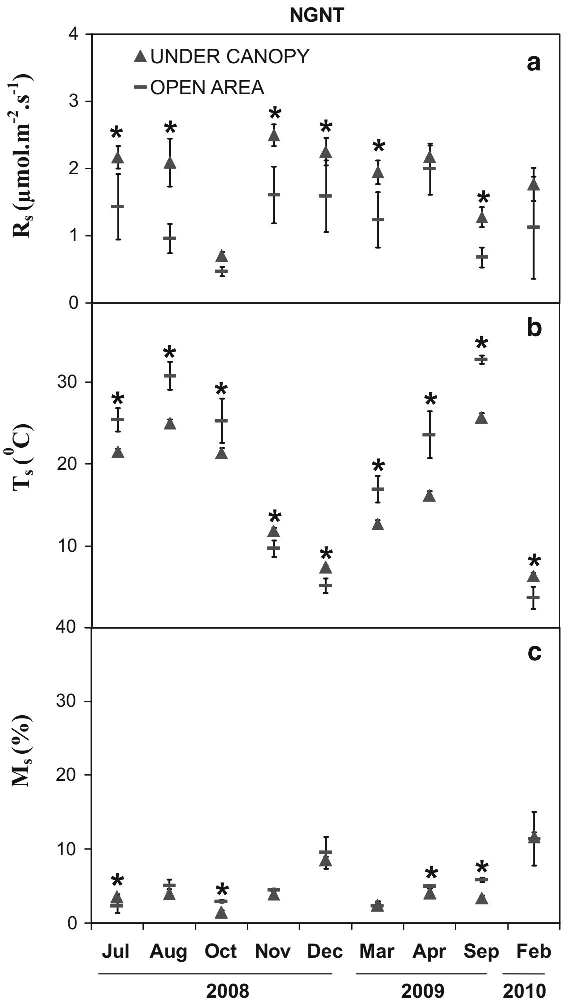

Fig. 4 Influence of canopy on **a** soil respiration (R_s μmol m^{-2} s^{-1}); **b** soil temperature (T_s °C); and **c** soil moisture (M_s %) in *NGNT*, non grazed-non tilled. *Asterisks* indicate significant differences between tree canopy and open areas

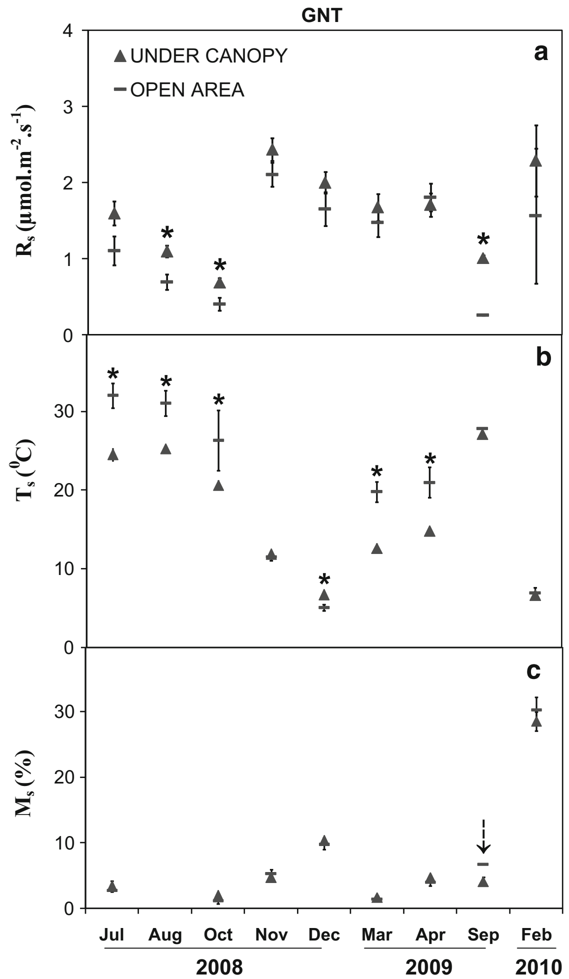

Fig. 5 Influence of canopy on **a** soil respiration (R_s μmol m^{-2} s^{-1}); **b** soil temperature (T_s °C); and **c** soil moisture (M_s %) in *GNT*, grazed-non tilled. *Asterisks* indicate significant differences between tree canopy and open areas and *discontinuous arrow* indicate significant effect at $p = 0.1$

This effect was fundamentally driven by R_s declines observed in the months of July 2008, August 2008, September 2009 and April 2009, three of which belong to the hot dry period, coinciding with cattle grazing. Decreases in R_s with grazing have been found previously (Bremer et al. 1998; Cao et al. 2004; Raiesi and Asadi 2006) in similar ecosystems. On the other hand, R_s increases (Lecain et al. 2000; Liebig et al. 2013) or a lack of a clear relationships between grazing and R_s have also been observed in other studies (Milchunas and Lauenroth 1993; Reeder and Schuman 2002).

For the most part, lower R_s values in grazed sites could not adequately be explained by simple changes in microclimate even though temperature and water availability were found to be the most important factors controlling soil respiration (Mielnick and Dugas 2000; Raich and Schlesinger 1992). In our data set, R_s was correlated with temperature and moisture, but not always and not consistently so. Higher temperatures resulted in reduced R_s rates across the entire data set, with the negative correlations somewhat stronger in grazing treatments. However, the relationship between temperature and R_s was inconsistent across seasons. In Mediterranean and semiarid ecosystems, soil moisture conditions can constrain the R_s responses to T_s and may account for large

Table 3 Mean values and standard errors of bulk density (Bd), C and N stock and C/N ratio in the top 10 cm of the soil for all treatments. *NGNT* non grazed-non tilled, NGT grazed-tilled, *GNT* grazed-non tilled and *GT* grazed-tilled obtained during the experiment (2008–2010) in *Dehesón del Encinar*

	NGT		NGT		GNT		GT	
	UC	OA	UC	OA	UC	OA	UC	OA
B_d (g/cm^3)	1.07 ± 0.02^a	1.16 ± 0.12^A	1.11 ± 0.03^a	–	1.05 ± 0.03^a	1.02 ± 0.08^A	1.03 ± 0.05^a	–
C stock (Mg/ha)	**9.57** ± 0.5^b	**3.76** ± 0.30^A	8.71 ± 0.6^b	–	**15.8** ± 1.08^a	**6.52** ± 1.30^B	9.29 ± 1.1^b	–
N stock (Mg/ha)	0.68 ± 0.03^b	0.29 ± 0.01^A	0.71 ± 0.06^b	–	1.32 ± 0.07^a	0.79 ± 0.14^B	0.68 ± 0.09^b	–
C/N	14.10 ± 0.27^a	14.97 ± 0.66^A	12.73 ± 0.39^b	–	11.87 ± 0.3^C	8.10 ± 0.86^B	13.71 ± 0.31^{ab}	–

Lower letters indicate significant differences between treatments at under canopy (UC) locations

Capital letters indicate significant treatments differences within open area (OA) and bold number indicate significant differences between under canopy and open area within a given treatment

differences in R_s between wet and dry periods (Davidson et al. 2000; Olsen and Van Miegroet 2010; Sulzman et al. 2005) and the greater role of soil moisture in controlling R_s especially during the warmer growing season. Our results were consistent with other Mediterranean systems (Hussain et al. 2009; Ma et al. 2007). Only during cold moist periods did T_s emerge as an important positive driver of R_s indicated by the Q_{10}, which ranged from 2.5 to 6. It is interesting to note that the undisturbed locations (NGNT) showed the highest sensitivity of R_s to T_s change, while this temperature sensitivity declined with disturbance through either tilling or grazing.

The grazing induced changes in R_s could not be ascribed to soil compaction, as our result did not shown any change in soil B_d after grazing. In general, the changes in B_d due to grazing depend on their intensity and soil characteristics. Light to moderate livestock grazing on well drained pastures (Greenwood and McKenzie 2001), rangelands (Gifford and Hawkins 1978; Trimble and Mendel 1995) and semiarid steppe (Steffens et al. 2008) were found to contribute little to long-term overall soil compaction as measured by soil B_d or water infiltration rate. Heavy grazing (Linnartz et al. 1966; Mapfumo et al. 1999) or grazing on wet soils (McNabb et al. 2001; Proffitt et al. 1993) often reduced water infiltration rates and soil moisture status, reduces air-filled porosity, and increases soil B_d, and surface soil hardness (Jia et al. 2007).

The lower R_s in the grazed treatment could also be related to differences in soil organic matter (SOM) characteristics (Reeder et al. 2004), such as lower inputs of decomposable SOM associated with export by grazing animals (Baron et al. 2002) and/or changes in plant species composition (Biondini et al. 1998; Raiesi and Asadi 2006; Taddese et al. 2002; Yates et al. 2000). Raiesi and Asadi (2006) found a decline in labile SOM due to grazing activities. In combination, the change in quality and quantity of litter input may have decreased soil microbial activity in the grazed sites. The herbage removal and the reduction in belowground translocation of carbohydrates (Bremer et al. 1998) has been noted to result in a reduction in weight of roots (Johnson and Matchett 2001) and root exudates, contributing to lower R_s in grazed places. Furthermore, Brady and Weil (2008) and Follet et al. (2001) found that water holding capacity in grazed sites of grassland ecosystems produces more stable aggregates of SOM, converting SOM in the grazing treatments into more stable, less decomposable soil C and N reservoirs.

Our results showed an average increase of 3 Mg/ha of C and 0.3 Mg/ha of N stocks due to grazing, consistent with results found by different authors in similar ecosystems (Bauer et al. 1987; Conant et al. 2005; Chaneton and Lavado 1996; Reeder and Schuman 2002; Schuman et al. 1999; Simón et al. 2012). Other author have observed no changes (Barger et al. 2004; Binkley et al. 2003) or decreases of soil C and N stocks (Abril and Bucher 1999; Frank 2005; Neff et al. 2005; Raiesi and Asadi 2006; Steffens et al. 2008) in response to grazing intensities. These differences in the responses of soil C and N stocks to grazing, possibly result from differences in climate, soil characteristics, landscape position, vegetation community, grazing management practices (Milchunas and Lauenroth 1993; Reeder and Schuman 2002);

seasonal grazing frequency, intensity and duration (Reeder and Schuman 2002). In addition, variability in livestock defecation and urination effects (Stark et al. 2000), or in soil sampling methodology could account for the different findings among reported studies (Schuman et al. 1999). From our results, we conclude that light grazing in our dehesa ecosystem did not have negative effects on the soil C and N reservoir capacity.

Tillage influences

The tillage treatment utilized in this experiment caused infrequent, moderate, and inconsistent responses in R_s. The significant decrease in R_s in November 2008 and increase in February 2010, coincided with similar variations in T_s in those months, combined with somewhat higher M_s content, again indicating the importance of M_s in this ecosystem (Joffre and Rambal 1988). The markedly higher R_s in the tilled sites in February 2010 might have been by the high precipitation during that month stimulating microbial activity in more exposed soils.

The limited effect of tilling on R_s across all data was also found by other authors (Alvarez et al. 1998; Ball et al. 1999; Reicosky and Lindstrom 1993) in similar ecosystems. Other studies have described higher R_s values under no-till than in ploughed soils (Franzluebbers et al. 1995; Jackson et al. 2003; Kessavalou et al. 1998) related to labile C accumulation and subsequent C mineralization in no-till soil (Alvarez et al. 1998). In other situations, the opposite pattern was observed (Alvarez et al. 2001; Álvaro-Fuentes et al. 2007; Bono et al. 2008; Ellert and Janzen 1999; Morell et al. 2010; Reicosky et al. 1997), attributed to a more intense C turnover in plowed soils (Franzluebbers 2002) or a slower residue decomposition rate under no-till (Fortin et al. 1996).

Our data reveal that tilling decreased C and N stocks on average by 3.5 Mg/ha and 0.3 Mg/ha, respectively, with stock declines most pronounced in the grazed sites. The interactions between grazing and tilling treatment suggests that positive grazing effect on C and N stocks might counteract the negative tilling effects, where both treatment coincide. Bono et al. (2008) also reported a higher soil C for in no-till compared to tillage treatment between 0 and 15-cm soil depth. Lopez-Garrido et al. (2009, 2011) reported reductions in soil C stocks in the first year after tillage and increases two years later. They related the initial C loss to an increase in microbial activity and R_s resulting from increased aggregate destruction and exposure with soil inversion. Tilling most likely exposed soil aggregates which, together with increases in M_s, caused a strong initial loss of organic matter that was, however, not detectable in R_s changes due to the time elapsed between tilling and R_s measurements.

Although different authors have reported increases in soil organic C under conservation tillage (reduced-minimum tillage, no-tillage) in Spain (Álvaro-Fuentes et al. 2008; Bescansa et al. 2006; Hernanz et al. 2002; López-Bellido et al. 1997), our observations show a slightly negative influence of tilling on soil C and N stocks in dehesa systems.

Tree and grazing interactions

The values of the soil C and N stocks and C/N ratio were similar to those found by other authors in dehesa ecosystem in Spain (Casals et al. 2009; Moreno and Obrador 2007; Moreno et al. 2007; Schuman et al. 1999; Simón et al. 2012). The greater accumulation of C and N in organic matter below the tree canopy (Breman and Kessler 1995; Gallardo 2003; Gallardo et al. 2000; Sharrow and Ismail 2004) could explain the higher R_s. Several authors have shown an improvement in fertility and nutrient availability beneath tree canopy (Escudero 1985; Gallardo 2003; Gallardo and Merino 1998; Gallardo et al. 2000; Joffre and Rambal 1993; Menezes et al. 2002; Moreno and Obrador 2007) caused by differences in biomass production (Gea-Izquierdo et al. 2009) and a change in microbial community (Saetre and Baath 2000) between below canopy and open areas. Animals attracted to tree shelter could contribute more to the redistribution of organic matter and nutrients in the soil profile, as suggested by the greater under canopy C accumulation in the grazed area.

The low R_s average values (μmol m^{-2} s^{-1}) in open areas relative to those under tree canopy agree with findings in a dehesa system (Casals et al. 2009) and in a Mediterranean forest (Almagro et al. 2009) in Spain. However, contrary to the C accumulation patterns grazing decreased the differences in R_s between below canopy and open areas in the dehesa, consistent with lack of tree effects in grazed sites in a Spanish dehesa (Casals et al. 2009). Thus, it may be difficult to separate tree canopy effects from grazing effects on soil properties in silvopastural systems.

The presence of a tree canopy modified soil microclimate, with changes in T_s more pronounced than changes in M_s. Lower T_s beneath canopy was found by Moreno et al. (2007, 2005) in similar ecosystem, and was attributed to shading by the tree canopy (Gea-Izquierdo et al. 2009). During the coldest months (November 2008, December 2008 and February 2010) T_s values were higher beneath the canopy, likely because the vegetation cover reduced heat loss from the soil. The decrease in M_s we observed under the canopy is in agreement with results by Cubera and Moreno (2007) and Gea et al. (2009) in the same ecosystem, but contradict the higher soil moisture under canopy found in the proximity of trees by Gallardo et al. (2003), suggesting that tree effects on M_s are variable and depend on the ecosystem type.

Conclusions

Dehesas are complex ecosystems where differences in vegetation cover, silvopastoral practices, and microclimate all interact to influence C storage in the soil and losses from the soils. Divergent responses relative to C sequestration potential to various treatments were obtained depending on whether changes in soil C accumulation patterns or periodic soil respiration rates were considered. This subtle difference among response variables may be important when assessing the impact of silvopastoral management practices in national or regional assessments.

Grazing increased soil C and N stocks, tilling reduced soil C and N stocks, and the combination of both had somewhat compensatory effects. Superimposed to these treatments was the spatial variability in C and N accumulation patterns reflecting tree distribution in dehesas. Sites below tree canopies (*Quercus ilex*, L) generally had higher soil C and N stocks, especially when the areas were actively grazed.

Results from this study further show that light grazing and tilling practices used in the studied dehesa system in Spain had a slight but non-consistent impact on soil respiration and soil microclimate during the study period. Grazing generally reduced R_s, despite higher C stocks, suggesting the differences in C quality and stability also contribute to CO_2 gas losses from dehesa; the impact of tilling on R_s was small, without a measurable interaction between the treatments. This resulted in annual C gas emission ranging from 650 to 750 g m^{-2} across all treatments. Where trees were located R_s, rates were generally higher, but grazing tended to decrease these differences between open and below canopy C dynamics.

The R_s responses to T_s and M_s were not always straight forward, and the grazing and tilling effect on the relationship between R_s and soil microclimate strongly depended on the climatic period. Soil moisture was important in constraining the temperature sensitivity of soil respiration, indicating that water availability is one of the major ecological factors in dehesa system.

In conclusion, this study revealed that silvopastoral management in dehesa systems is not incompatible with soil C conservation. Tilling alone had a negative effect on soil C and N store capacity in this system that could be compensated through grazing. Both grazing and tree canopy had a positive influence in the ability of soils to store C and N. The latter emphasizes the importance of the conservation of woodland and/or active afforestation (since natural regeneration is usually absent or scarce) in order to maintain the sustainability and improve C and N sequestration potential of dehesa ecosystems.

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