Plant Soil (2010) 327:57–70
DOI 10.1007/s11104-009-0031-0

REGULAR ARTICLE

Effects of soil management practices and irrigation on plant water relations and productivity of chestnut stands under Mediterranean conditions

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Received: 22 January 2009 / Accepted: 12 May 2009 / Published online: 2 June 2009

Abstract The effects of different soil management practices and irrigation on plant water relations, physiological response and productivity of chestnut stands in Northeastern Portugal were assessed during four growing seasons (2003 to 2006). Treatments were: conventional soil tillage up to 15–20 cm depth with a tine cultivator thrice a year (CT); no tillage with spontaneous herbaceous vegetation (NV); no tillage with rainfed seeded pasture (NP); and no tillage with irrigated seeded pasture (NIP). Results suggest that soil water availability was the most critical parameter for chestnut productivity over the study period. In all treatments, high predawn leaf water potentials (-0.40 to -0.55 MPa) were observed during the dry seasons of 2003, 2004 and 2006, showing no critical conditions for plant productivity, which is ascribed to water availability in deep soil layers. In contrast, in 2005, an extremely dry year, water potentials decreased and varied from -1.46 to -1.72 MPa in late summer, showing unfavourable conditions for nut production. Maintenance of spontaneous herbaceous vegetation without irrigation enhanced productivity of chestnut stands as compared with the conventional tillage system and the no tillage system with seeded pasture. Productivity in the soil watering system (NIP treatment) was not significantly different from that observed in the NV treatment. Therefore, studies on the irrigation strategy should be developed, in order to increase its efficiency especially in stands with young trees.

Keywords Agroforestry systems · *Castanea sativa* · Crop tree irrigation · Soil and plant water relations · Soil tillage · Soil water depletion

Abbreviations

CV	Conventional tillage
DHB	Diameter at Breast Height

Responsible Editor: Tibor Kalapos.

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h	tree height
NIP	No tillage with irrigated seeded pasture
NP	No tillage with rainfed seeded pasture
NV	No tillage with herbaceous spontaneous vegetation cover
P	Photosynthetic rate
Ψ_{wpd}	Predawn leaf water potential

Introduction

Chestnut plantations for fruit production are an important agroecosystem in Europe, where they occupy about 117,000 ha, especially in Mediterranean area, with 110,000 ha, representing 94% of total Europe and 33% of the total world chestnut area (FAO 2004). Nowadays, in Northern Portugal, these systems occupy an area about 25,000 ha, being responsible for about 84% of the total national nut production (INE 2005) and are an essential source of income for rural areas and an important feature of the landscape. As one of the most profitable productive systems of the region, there is a great concern about the intensive management practices which are commonly used in those plantations, such as soil tillage, fertilization, pruning and irrigation (Portela et al. 1999; Raimundo 2003; Martins et al. 2005). Some of these practices have been considered a threat for soil quality and system sustainability (Abreu et al. 1993; Martins and Abreu, 1997; Portela et al. 1999).

Soil tillage is commonly carried out three or four times a year with a tine cultivator to incorporate organic residues into the soil, destruct soil surface crust, control weeds and save soil water (Portela et al. 1999; Raimundo 2003). However, no significant advantages of conventional tillage have been observed regarding water saving and nut production, when compared with less intensive practices, such as no tillage with maintenance of spontaneous herbaceous vegetation (Raimundo 2003). Furthermore, several negative impacts have been reported for the conventional tillage system: (i) decrease of soil organic matter content and biodiversity; (ii) increasing risks of soil compaction, soil erosion and nutrient losses; (iii) damage to tree roots, which enhance the occurrence of ink disease induced by *Phytophthora cinnamomi* (Hogue and Neilsen 1987; Glenn and Welker 1989; Lipecki and Berbeć 1997; Martins et al. 1999; Portela et al. 1999; Marcelino et al. 2000). Therefore, it is crucial to identify the proper soil tillage systems in the chestnut plantations to improve their productivity and sustainability, and to ameliorate soil quality.

Water deficit is one of the main constrains to tree growth and biomass production in Mediterranean conditions given the scarce rainfall during the growing season, therefore creating a large water deficit from May to September (INMG 1991; SNIRH 2005). In a strongly seasonal dry climate, the long-term sustainability of these ecosystems may be further threatened by the regional effects of global warming, which are predicted to result in increases in the length, severity and frequency of summer droughts (Miranda et al. 2002). In these circumstances, water availability is a main concern of producers, and irrigation has been experienced by some of them, although in an empirical way and without evaluation of its effect on soil plant relationships and productivity. However, water is a scarce resource and competition for its use between different activities, such as agriculture, industry and municipalities is dramatically increasing (Fereres and Evans 2006; Pereira et al. 2002a and b). Moreover, impacts of irrigation on the environmental quality are also of great concern (Stigter et al. 2006), and improving water use efficiency should be encouraged to optimize the use of that limited resource.

Replacement of conventional tillage by no tillage system in cereal crops has been reported to increase soil water storage (Lyon et al. 1998). Also, competition for water in intercrops has been reported to be negligible or absent (Morris and Garrity 1993). In this context, less intensive soil management (with spontaneous herbaceous vegetation or seeded pasture) and water supply might positively affect the functioning and productivity of chestnut plantations. Therefore, an experimental trial was established in a chestnut plantation, in 2001, (i) to evaluate whether soil management practices, including irrigation, affect tree water relations, tree physiologic response and nut productivity, and (ii) to develop base guidelines for improvement and sustainable productivity of chestnut plantations growing under Mediterranean conditions.

Materials and methods

Site description

The study was carried out by an experimental trial established on a private estate, in October 2001, in Northeast Portugal, municipality of Macedo de Cavaleiros (41^o 35′N and 6^o 57′W, 700 m altitude). The climate is of Mediterranean type with cool and wet winters and warm dry summers. Considering the available climatic data for the meteorological station at Bragança (30 km far from the experimental site), for the period 1970–2000, the mean annual rainfall was 818 mm, mainly concentrated from October to May (85%) (Fig. 1). The monthly distribution of rainfall and reference evapotranspiration, according to Hargreaves (1975), is shown in Fig. 1, which illustrates the climatic water deficit in the experimental area during the summer period. The mean annual temperature was 11.9ºC (INMG 1991), and monthly mean air temperature ranged from 3.4ºC in winter (December) to 22.4ºC in summer (August).

The landscape of the study area is gently undulating with slopes varying from 0 to 4%. The soils in the experimental area are developed on schists (Siluric formation), and show an Ap horizon down to 20 cm depth, and a C horizon down to 50–90 cm, being mostly classified as Dystric Regosols (FAO 2006). As the underlying rock (schists) is fracturated (mostly vertically) and not compact, which facilitate rooting in deep layers, the rooting depth is commonly deeper than the C horizon. Texture of both horizons is mostly sandy loam to loam. Chemical characteristics strongly differ between the Ah and C horizons (Table 1). In the former, pH values (H_2O) range from 4.5 to 5.4 and contents of organic C and exchangeable base cations are low. In contrast, extractable P and K contents are high and reach 185 and 205 mg kg^{-1}, respectively; the high P content is related to heavy fertilizer application, while that of K is associated to the nature of soil parent material. The subsurface horizon (C horizon) shows extremely low contents of organic C and nutrients, and is much more acidic than the Ah horizon.

Experimental layout

In October 2001, an experimental system was installed in a 40 year old stand of *Castanea sativa* Miller (*Longal* cultivar) at a spacing 12×12 m. The average trunk diameter at breast height (DBH), crown projected area and height (h) of trees were 39.8 cm, 86.0 m^2 and 9.9 m, respectively. The experimental design consisted of four treatments: (a) Conventional soil tillage (reference or control) down to 15–20 cm depth with a tine cultivator thrice a year, that is, after fruit harvesting and litter fall to incorporate organic residues into the soil, in late winter to incorporate fertilizers, and in late spring for soil surface crust destruction and control weeds (CT); (b) No tillage with spontaneous herbaceous vegetation (NV); (c) No tillage with rainfed seeded pasture (25 kg seed /ha) (NP); and (d) no tillage with irrigated seeded pasture (NIP). Each treatment (replicated three times) was installed in plots randomly distributed in the experimental area, each one with 600 m^2 and six trees. At the beginning of the experiment the following fertilizers were applied: 5,000 kg of calcareous compost (80% $CaCO_3$; 19% $MgCO_3$), 1,000 kg of superphosphate (18%), 500 kg

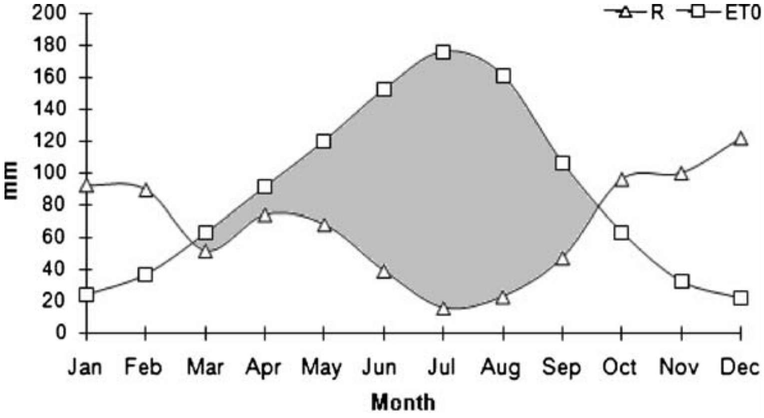

Fig. 1 Monthly average values for rainfall (R) and reference evapotranspiration (ET0) in the region of the experimental area, for the period 1970–2000. Gray colour area represents the climatic water deficit period

Table 1 Values of pH, and contents of organic C, extractable P and K, base cations and exchangeable acidity (EA) for surface and subsurface horizons of soils of the experimental area. Values correspond to means of six pedons

Depth	**Org C**	**P**	**K**	**pH**		**Ca**	**Mg**	**K**	**Na**	**EA**
cm	g kg^{-1}	mg kg^{-1}		H_2O	KCl		cmol$_c^+$ kg^{-1}			
0-20	15.3	185	205	5.1	3.6	2.19	0.54	0.50	0.04	1.05
20-50	4.1	4	99	4.6	3.3	0.95	0.36	0.22	0.03	3.17

of KCl, and 10,000 kg of organic fertilizer (50% of moisture, 69% organic matter; 1,5% N; 1,5% P_2O_5, 0,25% K_2O; 1,7% CaO; 0,3% MgO).

Irrigation (two sprinklers) was applied to three trees per plot, that is, nine irrigated trees were considered in the NIP treatment. The amount of irrigation water was 217, 78, 220 and 70 mm, which was supplied by 14, 7, 19 and 7 water applications in 2003, 2004, 2005 and 2006, respectively. In 2003, 2004 and 2005, the dates and volumes of irrigation were adopted according to the schedule of irrigation followed by the land owner, taking into account the rainfall and temperature during the summer period. For 2006, the irrigation was made only from 14 August to 15 September, taking as reference the minimum value of -0.6 MPa for predawn leaf water potential, and balancing the reference evapotranspiration to the experimental area conditions, calculated according to Hargreaves (1975).

In NP and NIP treatment plots, the pasture (a mixture of *Dactilis glomerata* L., *Lolium multiflorum* Lam., *Trifolium subterraneum* L., *T. repens* L., and *T. pratense* L.) was seeded in October 2001, using 25 kg ha^{-1} of the mixture, and covered by chisel, after spreading the seeds. In the NV treatment spontaneous herbaceous vegetation was mainly composed of *Chamaemelum mixtum* (L.) All., *Ornithopus compressus* L., *Rumex acetosella* L. subp. *angiocarpus* (Murb.) Murb. and *Vulpia bromoides* (L.) S.F. Gray. The vegetation in NV, NP and NIP treatments covered about 100% of the soil surface and was controlled by grazing and one cutting in late spring. Fertilization was the same for all treatments, as previously reported.

Measurements and samplings

Rainfall and air temperature were daily recorded in the experimental area during the study period, using an automatic weather station (DELTA-T Devices, Logger type DL2, with Software Ls2Win 1.0). The reference evapotranspiration (ET0) was estimated using the Hargreaves method (Hargreaves 1975), taking into account the available climatic data.

Volumetric soil water content (θ) was measured with a TDR device (Time Domain Reflectometry—Trase System, Soil Moisture Equipment), at 0–15 cm, 0–30 cm, 45 cm and 75 cm soil depth during the dry season. Measurements at the 0–15 and 0–30 cm soil layers were made with 15 cm and 30 cm length wave guides (Ref. 6008 L15 and 6008 L30 respectively), placed vertically, each one with 12 replications per treatment, that is, four in each treatment plot, while for those at 45 cm and 75 cm depth, buriable wave guides (model 6005 L2, Soil Moisture Equipment) were horizontally installed, with six replications per treatment (two per treatment plot). Devices were placed at middle distance between the limit of tree crown projection and the tree trunk. The measurements were carried out during the study period, generally once a week.

To assess the pattern of plant water uptake from soil profile, soil moisture content at 0–30 and 75 cm depth was compared with soil water content measured at -1.5 MPa pressure, that is, the threshold corresponding approximately to the wilting point (Brady and Weil 1999; Hillel 2004), on undisturbed soil samples of the same layers. This value has been used as a reference generally accepted for the wilting point of the majority of plants (Kramer 1969; FAO 1979; Marshall and Holmes 1988; White 2006). Sixteen undisturbed soil samples were taken at both 15 cm and 75 cm depths and processed at -0.033 MPa and -1.5 MPa pressure chamber apparatus.

Tree water status was assessed by measuring predawn (ψ_{wpd}) and midday (ψ_{wmd}) leaf water potentials with a Schölander-type pressure chamber (PMS 1000, PMS Instrument® Corvallis, Oregon, USA). Gas exchanges were estimated with an Infrared Gas Analyzer (IRGA, mod. LCA-2, Analytical Development *Co.*®, Hoddesdon, UK). For both studies, leaves were selected up to 3 m high from the external south facing side of the tree crowns. Twelve readings (four per tree) were made in each treatment plot at 7:00, 9:00, 11:00 and 13:00 from June to September in 2003, 2004 and 2006, and from August to September in 2005.

The amount of leaves and burs was evaluated through litter traps of 1 m^2 which were located under the canopy (two per tree) of three trees per treatment plot, that is, 18 litter traps per treatment. Nut production was estimated through the amount of fruits collected in three trees per plot (nine trees per treatment).

Statistical analysis

For soil moisture contents and physiological parameters, a one-way ANOVA and a post hoc test, by year and date, were performed to analyse treatments effect. For litterfall and nut production, the analysis of variance ANOVA was followed, considering as sources of variation the year and treatments, their interaction and the error effects (trees by treatment and year), with the correspondent post hoc test for year and treatment effects. In both cases the JMP (SAS, Institute Inc.) software and for the post hoc the Tukey HSD multiple comparison test (for a significance level $p<0.05$) were used.

Results

Climatic data

Taking into account the importance of water deficit and the framing of the present study, the rainfall data recorded in the experimental area were organized according to the growth years (October to September), and are reported in Table 2, considering separately the CT, NV and NP as non-irrigated treatments and the irrigated treatment, NIP.

Rainfall showed a wide variability during the study period. The total rainfall from October to May reached 1,154.1 mm, 644.9 mm and 631.5 mm for 2002/2003, 2003/2004 and 2005/2006, respectively. These values were higher than the reference evapotranspiration in all the treatments for the same period. In 2004/2005 rainfall for the same period was only 437.1 mm for both non-irrigated and irrigated treatments, being close to the reference evapotranspiration value (431.7 mm).

During the summer period (June-September), rainfall ranged from 133.7 mm in 2003 to 47.3 mm in 2006, while water deficit in the same period varied from 470.5 mm in 2003 to 582.5 mm in 2005, for the non-irrigated treatments, and from 253.5 mm in 2003 and 444.9 mm in 2006 for the irrigated treatment (Table 2).

In contrast to rainfall, monthly temperatures did not show strong differences among study years, and were close to the average for 1970–2000.

Table 2 Rainfall (R, mm), reference evapotranspiration (ETO, mm) and water deficit (R-ETO, mm) in the periods of October-May and June-September (the summer period) in non-irrigated (CT, NV, NP) and irrigated (NIP) treatments

Year	**Climatic Param**	**June - September**		**October-May**
		CT, NV, NP	**NIP**	**All Treatments**
2002-03	**R**	133.7	350.7	1,154.1
	ET0	604.2	604.2	443.8
	R-ET0	-470.5	-253.5	710.3
2003-04	**R**	93.5	171.5	644.9
	ET0	588.3	588.3	418.6
	R-ETO	-494.8	-416.8	226.3
2004-05	**R**	47.3	244.9	437.2
	ET0	629.8	629,8	431.7
	R-ETO	-582.5	-384.9	5.4
2005-06	**R**	93.5	163.5	631.5
	ET0	608.4	608.4	488.7
	R-ETO	-514.9	-444.9	142.8

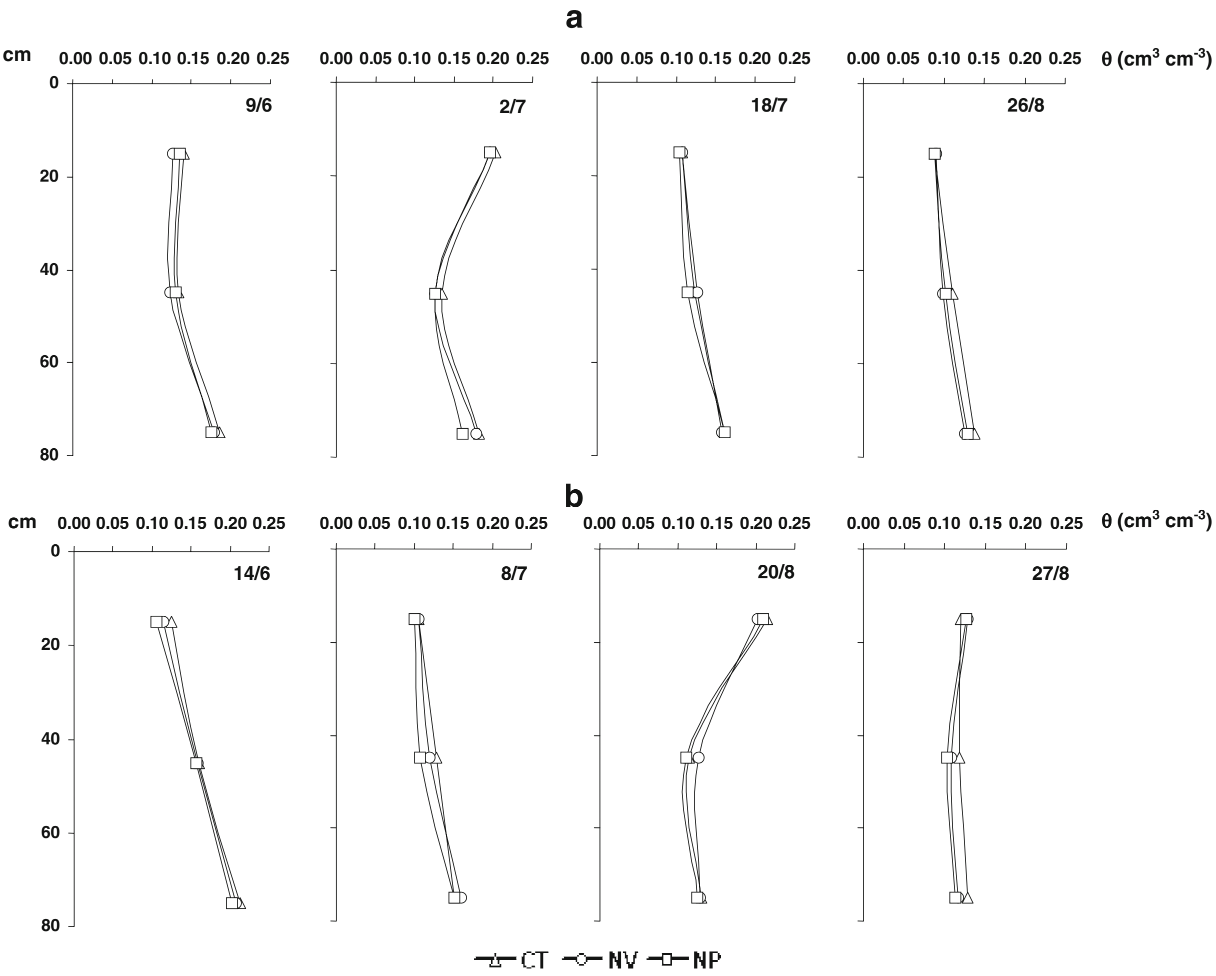

Fig. 2 Soil moisture (θ) content (cm^3 cm^{-3}) up to 75 cm soil depth, in CT, NV and NP treatment plots, in summer 2003 (A) and 2004 (B). Standard errors are too small to be shown. No significant differences were detected at the same date between treatments

Soil moisture regime

Values of soil moisture measured (in 2003 and 2004) to assess the effect of the conventional tillage and the no tillage systems on soil moisture content, with the maintenance of vegetation cover, are shown in Fig. 2. The results showed a general trend of no positive effect of conventional tillage (CT) on soil moisture content. In fact, soil moisture in this treatment was not significantly different ($p>0.05$) from the others. Also, moisture contents in the NP treatment (with rainfed seeded pasture) were similar to those measured in the treatment with spontaneous herbaceous vegetation cover (NV treatment).

The variation of available water for plants in the soil profile of CT plots (30 cm and 75 cm soil depth) along the drought period, in 2003, 2004, 2005 and 2006, as well as the values measured at -1.5 MPa (0.10 cm^3 cm^{-3} at 30 cm and 0.12 cm^3 cm^{-3} at 75 cm) and at -0.033 MPa (0.26 cm^3 cm^{-3} at 30 cm and 0.27 cm^3 cm^{-3} at 75 cm), corresponding respectively to the wilting point and to the field capacity, are shown in Fig. 3. Soil moisture content at the 30 cm soil depth (which was at summer beginning lower than the field capacity) tended to strongly decrease during the summer period, reaching contents lower than that measured at -1.5 MPa. However, a wide temporal variability was observed, as moisture contents much higher than those measured at -1.5 MPa were determined in August (in 2004 and 2006) in relation to rainfall events during the summer. Soil moisture contents measured during the dry season of

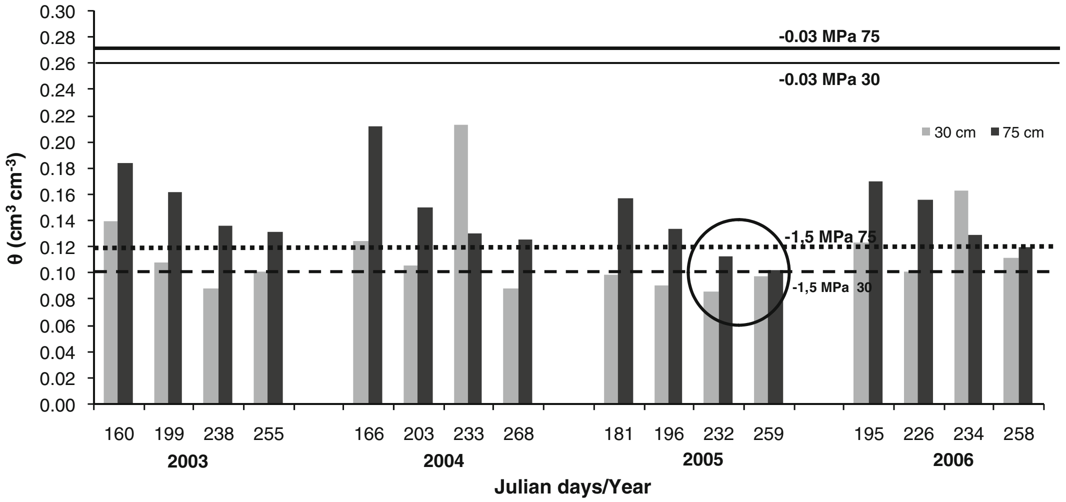

Fig. 3 Soil water content (θ) at 30 cm and 75 cm depth, measured in the summer period (Julian days) for the CT treatment, compared with soil water content measured at -1.5 MPa and–0.03 MPa on undisturbed samples from the same treatment. Circle indicates the very dry conditions in 2005

2005 showed small variation during the summer period and were consistently lower than that corresponding to the wilting point reference value.

The soil moisture content at the 75 cm depth was always below the field capacity and decreased during the drought period (Fig. 3). At the end of summer in 2003, 2004 and 2006, it was higher than that measured at-1.5 MPa. In contrast, in 2005, from August 2005 onwards, which followed a wet season with much less rainfall than the average (see Table 2),

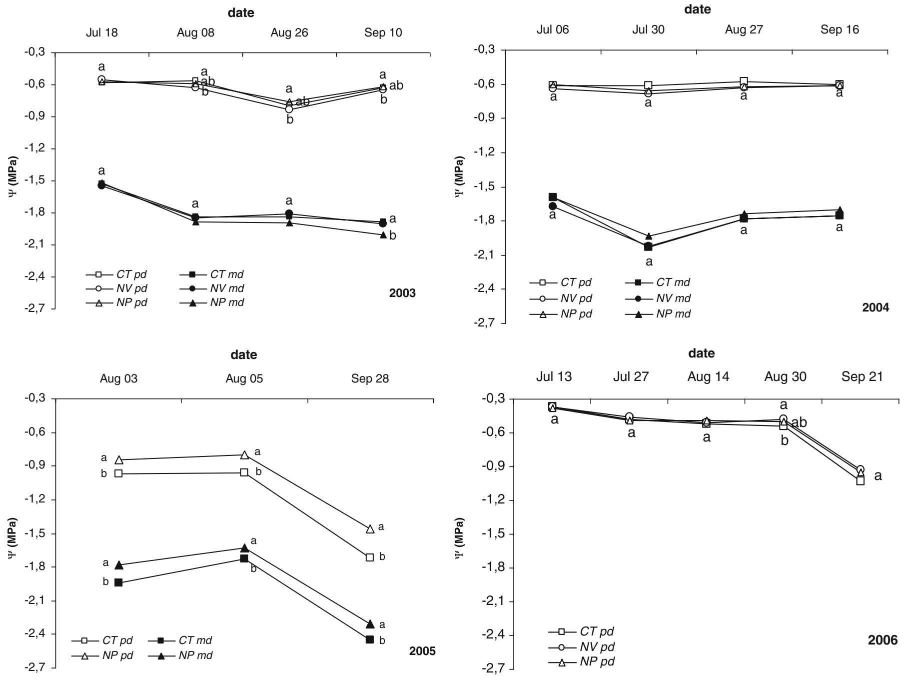

Fig. 4 Predawn (pd) and midday (md) leaf water potential measured in plots of CT, NP and NV treatments from June to September 2003–2006 (n=12). Different letters at the same date means significant differences ($p<0.05$) between treatments by the Tukey HSD multiple comparison test

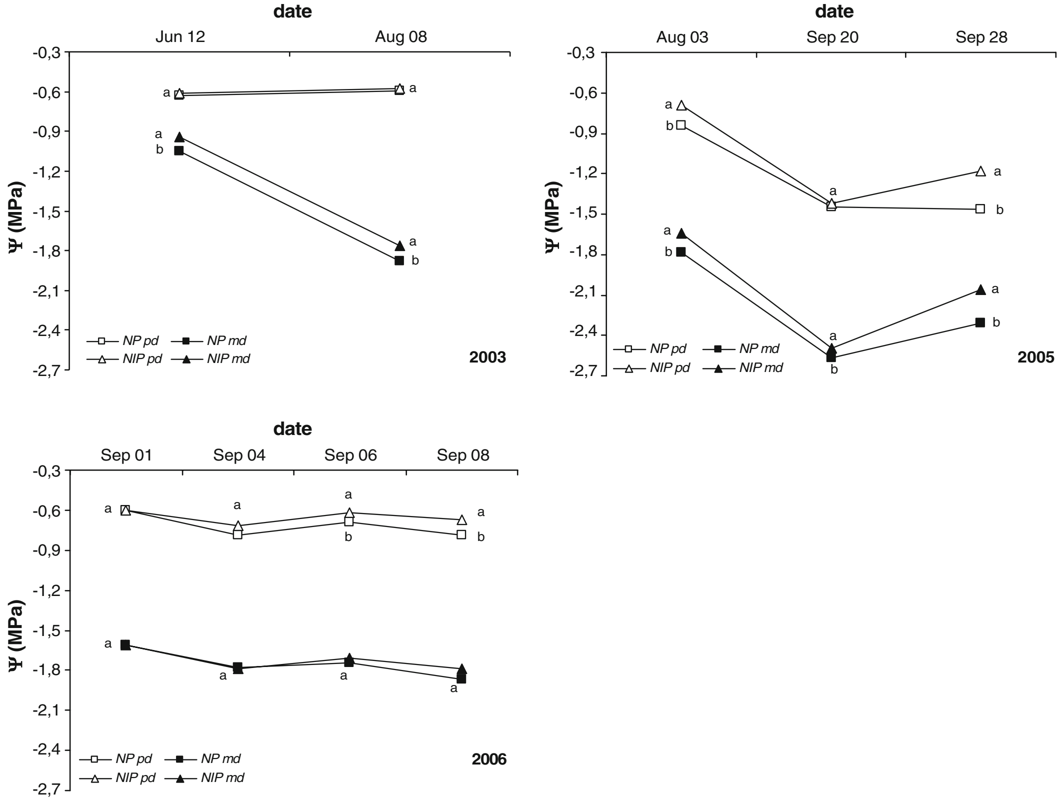

Fig. 5 Predawn (pd) and midday (md) leaf water potential (Ψ_W) measured in plots of the NP and NIP treatments in 2003, 2005 and 2006, from June to September (n=12). Different letters at the same date means significant differences ($p<0.05$) between treatments by the Tukey HSD multiple comparison test

the moisture contents were lower than the value measured at -1.5 MPa.

Predawn leaf water potential (Ψ_{wpd}) and photosynthetic rate (P)

The value of predawn leaf water potential (Ψ_{wpd}) was the parameter adopted in the present study to evaluate the .soil-plant-water relations which is illustrated in Figs 4 and 5. Treatments CT, NV and NP were used to compare the effect of conventional tillage versus maintenance of herbaceous vegetation cover (both natural and improved pasture), whereas NP and NIP treatments were considered, in order to observe the effect of irrigation in similar herbaceous vegetation cover.

Values of Ψ_{wpd} in the CT, NV and NP treatments (Fig. 4), during the dry seasons of 2003, 2004 and 2006, were similar and in most of the study period were close to the value observed at the beginning of the summer period. Values of Ψ_{wpd} ranged from -0.37 to -0.55 MPa, at beginning of July, and from -0.54 to -1.03 MPa, in late summer. In all treatments (in 2003 and 2004), midday leaf water potentials were of the same magnitude and ranged between -1.52 and -2.03 MPa.

In the driest year (2005), Ψ_{wpd} values in the CT treatment were significantly lower than in the NP treatment, and were much lower than in the above mentioned years (Figs 4 and 5). Values at the beginning of August varied from -0.80 to -0.96 MPa in the NP and CT treatments, respectively, while at the end of September were much lower (-1.46 and -1.72 MPa, respectively). A similar trend was observed for midday leaf water potential.

Relatively to the effect of irrigation, Ψ_{wpd} values in treatments with similar vegetation (NP and NIP, respectively without and with irrigation) showed a similar trend along the dry season (Fig. 5). Values in the NIP were significantly higher than in the NP only in the dry seasons of 2005 and 2006. In both NP and NIP treatments, midday leaf water potential showed a pattern similar to that observed for predawn leaf water potential.

Photosynthetic rate (P) values, for the average of three standard days of the summer period, in 2003, 2005 and 2006, for the NP and NIP (just after the irrigations) treatments are illustrated in Fig. 6. In 2003, P values were higher for the NIP than for the NP treatment, with significant differences at 11:00 (respectively 8.88 and 6.22 µmol $CO_2.m^{-2}.s^{-1}$) and 13:00 (respectively 6.84 and 5.85 µmol $CO_2.m^{-2}.s^{-1}$). No significant differences were observed in 2005 and 2006; however, in 2005, the P values showed a strong decrease in relation to 2003 and 2006. The highest measured values of P were 8.55–9.05 µmol $CO_2.m^{-2}.s^{-1}$, when temperatures ranged from 21 to 25ºC (2003 and 2006), decreasing to 5.58–6.84 µmol$CO_2.m^{-2}.s^{-1}$ for temperatures from 32.5 to 34.5ºC (2003 and 2006).

Production of leaves, burs and nuts

A wide inter annual variability on production of leaves and burs and nuts was observed. Litterfall and fruit production showed significant differences among years and treatments (Table 3), and influence of years as a source of variation (42.3 and 52.2%, respectively) was higher than that related to treatments (7.0 and 12.7%, respectively). Also, a considerable error effect, attributed to the influence of trees and site quality was observed (50.7 and 32.8%, respectively).

Dry matter production of leaves plus burs (Table 4) ranged from a minimum of about 317 g m^{-2} in 2005 to a maximum of 613 g m^{-2} in 2003. Values for the CT (440 g m^{-2}) and NP (486 g m^{-2}) treatments were significantly lower than in the NV (607 g m^{-2}) treatment. The lowest fruit production (9.2 kg $tree^{-1}$) was also observed in 2005, and was significantly different from that in the other study years (25.5 – 27.9 kg $tree^{-1}$). Production in the CT and NP (18.8 and 19.6 kg $tree^{-1}$, respectively) was significantly lower than in the NIP and NV treatments (24.4 kg and 27.2 kg $tree^{-1}$, respectively). As illustrated in Fig. 7, nut production between treatments in the driest year varied from 4 to 12 kg $tree^{-1}$ while ranged from 20 to 35 kg $tree^{-1}$ in 2004.

Discussion

The application of the no tillage system (with maintenance of spontaneous herbaceous vegetation cover) did not lead to negative effects on water content in the soil. This pattern is in agreement with observations in similar systems reported by Raimundo (2003) and Martins et al. (2005) in which no advantages of conventional tillage on water saving were observed, as compared with the maintenance of natural vegetation cover. This trend also agrees with results from studies developed on cereal crops (Bescansa et al. 2006) and olive orchards (Hernandéz et al. 2005), under semi arid climatic conditions,

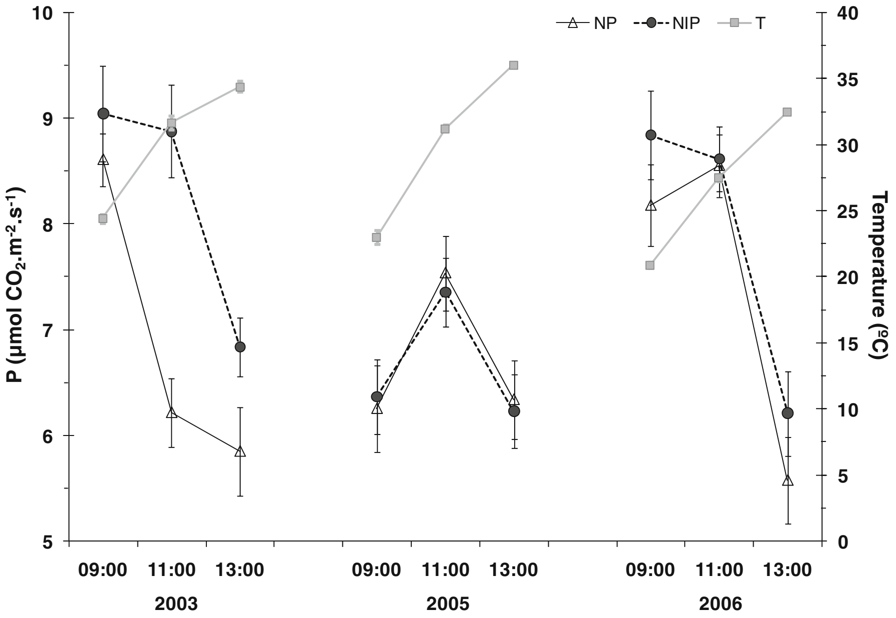

Fig. 6 Average values for daily (9 h, 11 h and 13 h) photosynthesis rate (P) in NIP and NP treatments and air temperature (T) for three standard days of summer period (n=36) in 2003 (12 June, 8 August, 12 September), 2005 (3 and 5 August, 20 September) and 2006 (16 August, 1 and 8 September). Bars show SE

Table 3 Analysis of variance related to the effect of years and treatments on litterfall and fruit production. No significant interactions are not shown

Source of variation	df	Mean square	F-value	P-value	Expected variation (%)
Litterfall					
Year (Y)	3	2,910.22	30.58	0.0001	42.3
Treatments (T)	3	564.76	5.93	0.0008	7.0
Error (trees/T/Y)	126	95.18			50.7
Nut production					
Year (Y)	3	632,177.58	55.09	0.0001	52.2
Treatments (T)	3	162,967.26	14.20	0.0001	12.7
Error (trees/T/Y)	120	11,475.71			32.8

where a positive effect of no tillage on soil water content and storage was observed when compared with tillage practices. Also, the installation of a pasture showed no effect on soil moisture when compared with the conventional tillage system (CT treatment). We may emphasize that in the no tillage system the vegetation cover may partially be controlled by the build up of organic layers on the soil surface, as reported by Raimundo et al (2008). Similar soil water contents in the NV and CT treatments may be also explained by small variations in soil organic matter contents, which were reported by Raimundo et al. (2008) in a previous study (8-year period) in the same region.

Our results indicate that water availability in the soil profile is mostly dependent on weather conditions regarding rainfall distribution. Although in the four year study period soil moisture contents, at the 30 cm soil depth, lower than that measured at -1.5 MPa were observed, values measured in the dry season of the driest year (2005) were consistently lower than this reference value. However, soil moisture contents much higher than that corresponding to the wilting point were obtained in certain summer periods (see Fig. 3), which were related to rainfall events during summer. As the drought period progressed, an increasing proportion of water was extracted from deeper soil layers, confirming previous studies (Garnier et al 1986). However, soil moisture content at the 75 cm depth during drought seasons only reach the value measured at -1.5 MPa (the threshold corresponding to the wilting point: Brady and Weil 1999; Hillel 2004) in the driest year of the study period. This pattern is in agreement with the wide differences between rainfall and reference evapotranspiration observed during the October-May periods (5–710 mm; see Table 2), indicating that strong decreases in rainfall during such periods may negatively affect the replenishment of water retention capacity of deep soil layers.

In the present study, Ψ_{wpd} values showed a small variation during the drought season, following the pattern reported by Cubera and Moreno (2007) and Moreno et al. (2007) for *Quercus ilex* trees growing in a drier site (precipitation: 500–600 mm), with deeper soils and lower tree density (9–35 trees/ha). However, our results are not in total agreement with those reported by David et al. (2007) for both *Q. ilex* and *Q. suber* stands (about 30 trees/ha) under Mediterranean conditions in southern Portugal (665 mm, 15Cº), in which much lower values (-1.7 to -2.3 MPa) were observed in summer. Only in the driest year (2005) Ψ_{wpd} values (-0.7 to -1.7 MPa) were close to those measured by David et al. (2007), which agrees with

Table 4 Litterfall (g DM m^{-2} of leaves + burs) and fruit (kg DM tree^{-1}) production according to years and treatments during the study period

Year	n	Mean ± SE	Treatment	n	Mean ± SE
Litterfall					
2003	36	612.6±20.7 c	CT	32	440.0±28.5 a
2004	36	573.3±20.7 bc	NP	34	485.6±27.7 ab
2005	36	316.7±20.7 a	NPI	36	501.0±26.9 b
2006	28	541.7±23.4 b	NV	34	606.5±27.7 c
Nut production					
2003	39	27.9±1.6 b	CT	34	18.8±2.1 a
2004	36	25.5±1.7 b	NP	37	19.6±2.0 a
2005	36	9.2±1.7 a	NPI	36	24.4±2.1 b
2006	31	27.8±1.8 b	NV	35	27.2±2.1 b

Different letters in the same column means significant differences ($p<0.05$) between years or treatments by the Tukey HSD multiple comparison test

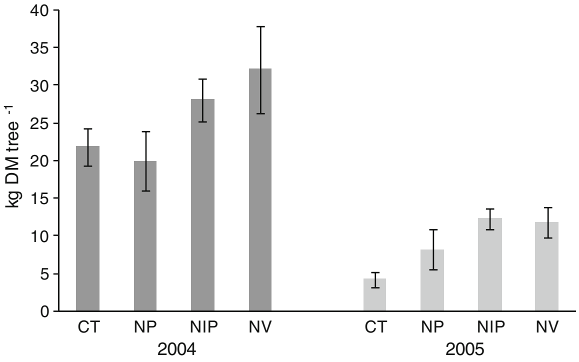

Fig. 7 Nut production (kg DM per tree) in the different treatments for 2004 and 2005 (n=9). Bars show SE

the low soil moisture content observed in both surface and deep soil layers. Our Ψ_{wpd} results indicate that trees were consuming a high volume of water for transpiration during the drought period. Given the high tree density in chestnut plantations (about 70 trees/ha), higher Ψ_{wpd} values than in the above mentioned *Q. ilex* stands are found to be unexpected. In addition, the amount of available water in the soil up to the 75 cm depth at the beginning of the summer was negligible; for instance, in 2003 and 2004 it was less than 5 mm. Therefore, the high Ψ_{wpd} values observed in the present study during the drought season may be mostly explained by the water uptake from deeper layers of the soil and soil parent material. It means that chestnut trees, as reported for evergreen oak trees (e. g. *Q. suber* and *Q. ilex*) in climates with seasonal drought (Bréda et al. 1995; Breman and Kessler 1995; Canadell et al. 1996; Otieno et al. 2006; David et al. 2007), rely on deep roots and the ability to uptake water from sources in the subsoil including permanent water tables. It is also evident that chestnut trees may have a deep root system facilitated by the fractured nature of the rock (schists), as reported by David et al. (2007) for *Q. ilex* trees, in southern Portugal. However, further studies on chestnut root system and the evidence of water tables are needed for a better understanding of the water use pattern by chestnut plantations.

Values of Ψ_{wpd} in the conventional tillage system were similar to those in rainfed treatments with vegetation cover (NV and NP), indicating that herbaceous plant cover (either natural or rainfed improved pastures) may have no negative effects on soil and plant water status or tree water relationships. This trend is supported by findings of Gakis et al. (2004), in a study of understory effects on early stage trees growing with *Acer pseudoplatanus* and *Pinus sylvestris*. These authors reported that understory species cover, in Mediterranean conditions, can compete with trees in the early stage after plantation, but as the root system of trees goes deeper, mature trees are less dependent on water competition by herbaceous vegetation of surface soil layers. In the present study, treatments were installed in chestnut mature stands where tree root systems were mostly located below 20 cm soil depth due to root damage through harrowing operations, as reported by Raimundo (2003). Therefore, a certain degree of spatial separation between herbaceous plants and trees may occur, following the trend observed by Cubera and Moreno (2007) for holm oak stands in Spain, where herbaceous roots are mostly in the upper 30 cm of soil (Moreno et al. 2005). As chestnut trees have a high reliance on deep water, it seems that trees and herbaceous vegetation are, for the most part, consuming water from different soil layers, thus preventing below ground competition. Moreover, rainfed improved pastures, as reported for vineyards (Morlat and Jacquet 2003; Celette et al. 2008) and dryland agroforestry (Lehmann et al. 1998), may also force the tree root system to explore deeper soil layers, thus partly preventing direct competition for water resources.

Tree water status in irrigated plots (NIP treatment) followed the same pattern and showed small differences regarding the rainfed treatment with similar vegetation (NP). This suggests a negligible effect of the irrigation system on soil and tree water status (Fig. 7) and that the irrigation water supplied was not sufficient to alleviate the deficit of available water in deep soil layers. However, this trend disagrees with that reported by Gomes-Laranjo et al. (2006) for young almond trees, under similar irrigation system, where a positive response of Ψ_{wpd} and P values to irrigation was observed. Such a difference may be attributed to the fact that almond trees were young and growing in the absence of herbaceous vegetation, and therefore with a root system still dependent on the upper soil layers. We may underline that, independently of leaf water potential and soil water availability, the photosynthetic rate sharply decreased when air temperature increased to 33ºC. These data are consistent with previous studies (Gomes-Laranjo et al. 2005), in which the P of *C. sativa* was shown to be dependent on air temperature, but independent of soil management.

Despite similar Ψ_{wpd} values in the CT and NV treatments, nut production was significantly lower in the former than in the latter, corroborating results reported by Raimundo (2003) in the same region. The advantage of the no tillage system with spontaneous herbaceous vegetation may be associated with the fact that the damage of the tree root system is avoided and organic C losses reduced. Also, the build up of soil organic layers, as reported by Raimundo et al. (2008), creating a mulching effect, may increase soil organic matter content and reduce soil erosion risks (Bescansa et al. 2006). This and the occurrence of a herbaceous vegetation cover may also improve soil surface structure, change pore-size distribution, increase permeability as compared with the conventional system, and favour water soil replenishment during the winter, as reported for vineyards in southern France (Celette et al. 2005). However, the nut production in the no tillage system with seeded pasture was significantly lower than that observed in the no tillage system with spontaneous herbaceous vegetation. This may be related to greater amounts of herbaceous vegetation in the former than in the latter (2.4 and 0.8 t DM ha^{-1}, respectively, as reported by Raimundo, 2003, in a previous study), and to the fact that seeded pasture (with leguminous species) may be more competitive for water resources than spontaneous species as concluded in a study with walnut trees (Dupraz et al. 1998). However, long term studies are needed to evaluate how competition patterns are balanced by the improved soil organic matter and nitrogen status in the seeded pasture system.

Inter annual variation in nut productivity was much stronger than that related to management systems, in relation to the wide variability of weather conditions regarding rainfall (see Tables 2 and 4). This is in line with findings of Raimundo et al. (2008) who showed that chestnut productivity is positive and strongly related to the rainfall during the October-May period. In addition, differences between treatments regarding productivity were stronger in the driest year (2005), when significant differences in Ψ_{wpd} values between the conventional and the no tillage systems were observed (see Figs. 4 and 7). For instance, nut production in this year under the conventional tillage system was only 35–62% of that measured in the other treatments (see Fig. 7), while in 2004 it attained 68–110%. This suggests that the traditional tillage is more deleterious to the system under prevailing conditions of severe drought. Thus, taking into account nut production and the projection in increases in length, severity and frequency of summer droughts (Miranda et al. 2002), conventional tillage should be replaced by conservative practices (e.g. no tillage with spontaneous vegetation cover) to maintain the long-term sustainability of the chestnuts stands in Northern Portugal.

Although irrigation treatment (NIP) led to higher nut production than in the CT and NP treatments, it did not show any advantage when compared with the NV treatment (Table 4), which is in agreement with the similar predawn leaf water potentials observed in both treatments (Figs 4 and 5). This suggests that the irrigation schedule followed in the NIP treatment, that is, the supply of water affecting only the top soil layer, did not lead to an enhancement of soil water availability during summer drought and was ineffective on nut production. In chestnut stands, as in deepwater-dependent ecosystems (Cooper et al. 2003), plant water stress, leaf shading and even tree mortality may increase when deep water resources decline, as observed in 2005. Therefore, as for Mediterranean evergreen ecosystems, the main threat for chestnut systems comes from the enhanced severity of summer drought caused by climate change. For instance, the severe drought of 2005 led to a strong decline in tree gas exchange as observed for southern regions of Portugal (David et al., 2007). In this context, the scarcity of water resources may lead to increased groundwater extraction for human use, which further aggravates the climatic effects on groundwater resources, with strong negative impacts on the sustainability of chestnut ecosystems, since these trees seem to be strongly dependent on subsoil water sources. Therefore, the use of irrigation system is questioned and the development of other strategies of irrigation application in order to enhance its efficiency is needed.

Conclusions

Weather conditions, especially rainfall, showed a wide variation during the study period with implications on the water storage in the soil profile and on the physiological responses of chestnut trees. Soil water storage in deep layers played an important role in water uptake by trees, which requires the capability of deep root development to assure the resistance to drought. Although the global scenario of increasing temperature may affect chestnut productivity, it is mostly related to the occurrence of erratic and extremely dry years. The use of irrigation with seeded pasture does not have clear advantage on soil water regime, tree physiological response and nut production, which indicate the need to develop new irrigation strategies to increase water use efficiency. No tillage and maintenance of spontaneous herbaceous vegetation, with lower requirements for water over improved seed pasture, seems to be at the moment the most favourable management system to assure productive sustainability of chestnut stands.

Acknowledgements The authors thank to the European project MANCHEST (Contract QLK5-2001-00029), PROCAST project (No 391 of AGRO program), which supported this study. José Lousada is acknowledged for assistance in statistical analysis. A special thanks to Professor Salvatore Leonardi coordinator of the first project, who passed away on 2004 summer, for his enthusiasm and contribution to chestnut ecology research.

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