

Management of chestnut plantations for a multifunctional land use under Mediterranean conditions: effects on productivity and sustainability

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Abstract Chestnut plantations for fruit production in Northern Portugal have been subjected to intensive management system, including soil tillage, mineral fertilization and pruning. Some of these practices have no positive effect on productivity and soil–plant–water relations. Other systems (e.g., no tillage with maintenance of grass cover) have been adopted, aiming a multifunctional land use, exploiting nuts, pasture and edible mushrooms. Thus, an experimental trial was installed to assess the effects of such systems on productivity, sustainability and annual net income, as compared with the conventional system, over a six-year period. The treatments were: conventional soil tillage (CT); no tillage with permanent spontaneous herbaceous vegetation cover (NV); no tillage with permanent rainfed seeded pasture cover (NP); and as NP but with irrigation (NIP). Production of nuts, forage and edible mushrooms were measured

and sustainability was assessed by production and diversity of fungal sporocarps. Annual net income was estimated by the difference between the annual gross outputs (market values for nuts, forage and edible commercial mushrooms) and the annual input costs. The greatest nut and edible mushroom production and sporocarp biodiversity were achieved in the NIP and NV and the smallest in the CT treatment. The highest annual gross output was estimated for the NV and NIP treatments, whereas the highest annual net income was obtained for the NV. No tillage with maintenance of spontaneous grass cover showed to be the most favourable management system, as it has increased productivity and biodiversity.

Keywords Agroforestry systems · Biodiversity · *Castanea sativa* · Economics · Edible mushrooms · Silvopastoral systems · Soil management

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Abbreviations

CT	Conventional tillage
D	Fruit diameter in frontal view
d	Fruit diameter in lateral view
DM	Dry matter
FU	Feed units
FW	Fresh weight
h	Fruit height
NV	No tillage with herbaceous spontaneous vegetation cover
NP	No tillage with rainfed seeded pasture
NIP	No tillage with irrigated seeded pasture

Introduction

Chestnut plantations for fruit production are an important agroecosystem in Northern Portugal, occupying near 25,000 ha, producing 28,000 Mg of fruit (84% of the total national nut production) (INE 2005) which represents an essential source of income for rural areas. Several studies have been carried out to assess the effect of different soil management systems on tree water relations and physiologic response, productivity and pathology (Abreu et al. 1993; Martins and Abreu 1997; Portela et al. 1999; Marcelino et al. 2000; Raimundo 2003; Martins et al. 2005). No advantages of conventional system (soil tillage three a year) were then observed on fruit production and water saving, as compared with the no tillage with maintenance of herbaceous vegetation cover. Also, negative impacts of conventional tillage have been detected such as decrease of soil organic matter content, increasing risks of soil compaction, soil erosion, and nutrient losses and damage of tree roots, which enhance the occurrence of ink disease induced by *Phytophthora cinnamomi* (Hogue and Nielsen 1987; Glenn and Welker 1989; Lipecki and Berbeć 1997; Martins et al. 1999; Portela et al. 1999; Marcelino et al. 2000). These effects have been considered as responsible for the decline of chestnut plantations (Abreu et al. 1993; Martins and Abreu 1997; Portela et al. 1999).

Some studies showed that conventional tillage is more deleterious to chestnut orchards under conditions of severe drought, as compared with the maintenance of natural vegetation cover (Raimundo 2003). The tillage system with maintenance of herbaceous vegetation has been reported as a favourable management system to assure productive sustainability and soil quality in Mediterranean agroecosystems such as vineyards (Morlat and Jacquet 2003; Celette et al. 2005) and olive orchards (Hernández et al. 2005; Ramos et al. 2010).

These trends encouraged new strategies of soil management within a multifunctional prospect land use system, taking into account the advantages of grass cover, e.g., increased organic matter, biodiversity and soil permeability and reduced soil erosion hazard (Celette et al. 2005). Silvoarable and silvo-pastoral systems have been identified as the potential for biological species richness and protection against erosion, reducing agrochemical inputs and increasing

the overall resource-use efficiency of the system (Vandmermeer 1989; Jose et al. 2004; Eichhorn et al. 2006). Such systems provide both market (food, wood products, and fodder) and nonmarket goods and services (soil conservation, water and air quality improvement, biodiversity and scenic beauty), contributing to the rural economy and environmental protection (Alavalapati et al. 2004).

System sustainability maintenance is associated with soil quality and biological activity is recognized as a soil quality indicator, given its close relation to water and nutrient availability, soil aeration, biomass production, and its exceptionally sensitivity to changes in soil conditions (Doran and Zeiss 2000). Therefore, microbial diversity and functional groups of soil fauna are included as indicators for soil quality monitoring (Nortcliff 2002; Schloter et al. 2003). Within soil microbial communities, beneficial saprotrophic and mycorrhizal fungi are critically important soil biotic components in agroecosystems by the positive effects on plant nutrition (Smith and Read 1997), drought tolerance (Garbaye 2000) and protection against root diseases, such as chestnut ink disease (Branzanti et al. 1999). Environmental and soil conditions are particularly important in the development of fungal mycelial and sporocarps (Wiklund et al. 1995; Martínez de Aragón et al. 2007) as fungal species vary in their response to disturbance (Martín-Pinto et al. 2006). Therefore, fungal sporocarps occurrence, mainly ectomycorrhizal fungi, have been used as indicator of soil conditions or disturbance effects on below-ground ecosystems (Termorshuizen and Schaffers 1991; Luoma et al. 2004).

Differences on fungal communities between conventional and no-tillage systems were reported, being no-tillage systems generally more favorable to soil fungi (Beare et al. 1997; Frey et al. 1999). Management practices which promote the beneficial roles of the soil fungi will be essential for sustaining the productivity and ecological integrity of the chestnut orchards. Furthermore, some fungal species produces edible sporocarps, highly prized and only gathered in the wild, which have become an important income on rural areas (Arnolds 1995; Boa 2004). The most valuable and appreciated wild mushrooms in Portugal belongs to the group *Boletus edulis* s.l., comprising the species *Boletus edulis* Bull.: Fr., *Boletus aestivalis* Fr., *Boletus aereus* Bull.: Fr., and *Boletus*

pinophilus Pilát et Dermek. These species are ectomycorrhizal symbionts of chestnut trees and abundant in Mediterranean regions, with a great potential for management (Salerni and Perini 2004).

In this context, chestnut producers are motivated to change the conventional cropping system by the no-tillage system and maintain both rainfed and irrigated grass covers within a multifunctional chestnut orchards use, exploiting nuts, pastures and edible mushrooms. Therefore, to formulate management guidelines for the sustainability of these systems, a field experiment was developed to evaluate the implications of the different soil management systems on: (i) the production and quality of nuts, forage and edible mushrooms; (ii) sustainability, using mushroom productivity and fungal diversity as a soil quality bioindicator; and (iii) annual net income. Results from 2003 to 2008 are reported and discussed.

Materials and methods

Site description

The study was carried out by an experimental trial established in a private estate, in October 2001, in Northeast Portugal, municipality of Macedo de Cavaleiros (41°35'47"N and 6°57'44"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 (85%) from October to May (Fig. 1). The monthly distribution of rainfall and reference evapotranspiration, according to Hargreaves (1975), is shown in the Fig. 1a, which illustrates the climatic water deficit in the experimental area during the summer period. The mean annual temperature was 11.9°C (INMG 1991), and monthly mean air temperature ranged from 3.4°C in winter (December) to 22.4°C in summer (August).

During the study period, temperature was within the pattern of the reference period (1970–2000). The mean annual rainfall values for the study years and for the reference period 1970–2000, considering for each year the growing season (November to October), are also represented in Fig. 1b. As illustrated there was a high interannual fluctuation on total annual rainfall, being 2005 and 2008 the years with the lowest values and 2003 with the highest one. Also it was observed a high heterogeneity among years in rainfall distribution over the year (Fig. 2a, b).

The landscape of the study area is gently undulating with slopes varying from 0 to 4%, and geology made up schists (Siluric formation). The soils are mostly classified as Dystric Regosols (FAO 2006), sandy loam to loam, pH value in the upper horizon (Ap) ranging from 4.5 to 5.4, low contents of organic C and exchangeable base cations and high contents of extractable P and K, due to mineral fertilization. The subsurface horizon (C horizon) shows extremely low contents of organic C and nutrients, and is much more acidic than the Ap horizon (Table 1).

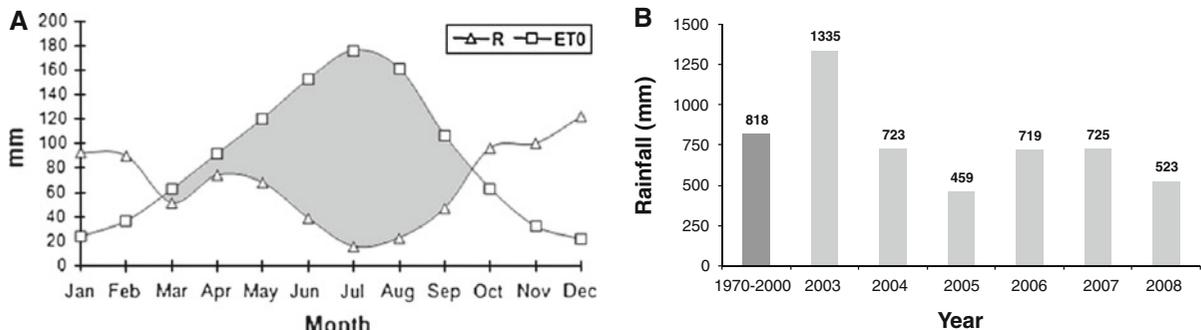


Fig. 1 Rainfall data for the region of the experimental area: **a** monthly average values for rainfall (R) and reference evapotranspiration (ET0), *gray* colour area representing the

climatic water deficit period; **b** Mean annual rainfall for the reference period 1970–2000 and for the study years

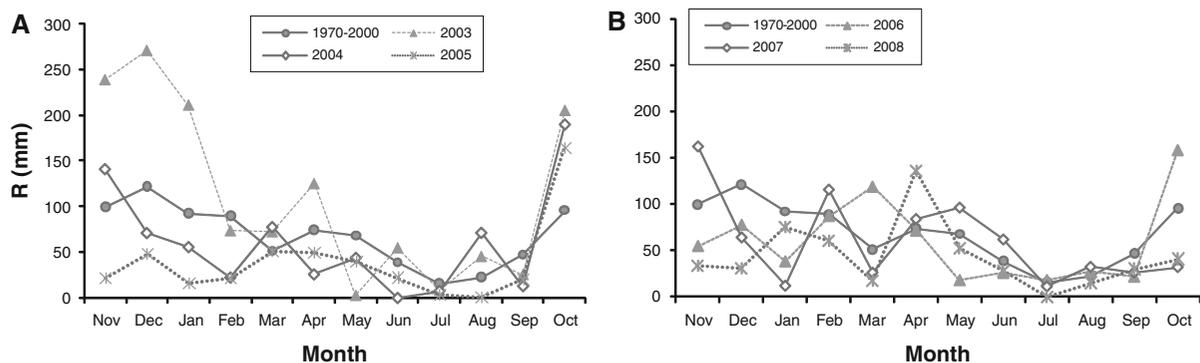


Fig. 2 Monthly average rainfall for the growth reference period (1970–2000), from 2003 to 2005 (a) and 2006 to 2008 (b)

Experimental layout

In October 2001, an experimental system was installed in a 40 year old stand of *Castanea sativa* Miller (*Longal* cultivar) at $12 \times 12 \text{ m}^2$ spacing. Average trunk diameter at breast height, crown projected area and height of trees were 39.8 cm, 86.0 m^2 and 9.9 m, respectively. Percentage of area beneath tree crowns was 72.4% and in the open 27.6%. 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 and maintenance of soil surface with spontaneous herbaceous vegetation (NV); (c) No tillage and maintenance of soil surface with rainfed seeded pasture (25 kg seed/ha) (NP); and (d) as NP but with irrigation (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 in all the treatments: 5,000 kg of limestone (80% CaCO_3 ; 19% MgCO_3), 1,000 kg of superphosphate (18%), 500 kg of KCl (60%) 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 NIP treatment. The irrigation schedule and volumes were according Table 2.

In 2003, 2004 and 2005, dates and irrigation volumes 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 2006–2008, irrigation was applied when a minimum value of -0.6 MPa for predawn leaf water potential was achieved, which was observed as a limit value for favourable vegetative conditions to the study species (Martins et al. 2005) and balancing the reference evapotranspiration (Hargreaves 1975) for the experimental area conditions.

In NP and NIP treatment plots, the pasture (a mixture of *Dactylis 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, covered by chisel, after spreading the seeds. In the NV treatment spontaneous herbaceous vegetation was mainly composed by *Chamaemelum mixtum* (L.) All., *Ornithopus compressus* L., *Rumex acetosella* L. subsp. *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 grazed by sheep herds.

Data collection

Nut production was quantified from 2003 to 2006, through the amount of fruits collected in three trees per plot (nine trees per treatment). To estimate the production, 70 trees per ha were taken into account, with $12 \times 12 \text{ m}^2$ spacing. Nut quality was assessed by the fruit weight (g fruit^{-1}) and a size index

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

Depth (cm)	Org C (g kg ⁻¹)	P (mg kg ⁻¹)	K (mg kg ⁻¹)	pH		Ca (cmol _c ⁺ kg ⁻¹)	Mg (cmol _c ⁺ kg ⁻¹)	K (cmol _c ⁺ kg ⁻¹)	Na (cmol _c ⁺ kg ⁻¹)	EA (cmol _c ⁺ kg ⁻¹)
				H ₂ O	KCl					
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

Values correspond to means of six pedons

Table 2 Dates of first and last irrigation, number of irrigations and water volume per year

Year	First irrig	Last irrig	Number	Water volume (mm)
2003	Jun 09	Sep 26	14	217
2004	Jun 15	Sep 21	8	78
2005	Jun 30	Oct 01	10	220
2006	Aug 01	Sep 20	7	70
2007	Jul 31	Sep 21	5	83
2008	Aug 25	Oct 06	6	77

$[(D+d+h)/3, \text{mm}]$, where D is the fruit diameter in frontal view, d is the fruit diameter in lateral view and h is the fruit height (Botu et al. 1999). Both parameters were also measured from 2003 to 2006, and for fruit weight and size, 180–270 fruits and 64–90 fruits, respectively, were used per treatment per year.

Forage production was measured (2006–2008) by weighting the dry matter in a frame of 0.5 m², with three replicates by plot both beneath canopy and open areas, nine replications per treatment, three times a year (beginning spring, middle June, and late autumn). Average forage and mushroom production by hectare was estimated taking into account the percentage of area out and under tree crowns.

Mushroom productivity and diversity were assessed through sporocarps surveys, from 2006 to 2008. Sporocarps were collected weekly, during the spring (May–July) and autumn (September–November) fruiting seasons (15 samplings per year), under tree crown of three trees per plot (nine trees per treatment), focusing on sampling units that are more likely to be important in obtaining a precise estimate of the productivity (Lund 1998). In 2006, sporocarps were also collected in the open and the respective percentage (20%) regarding the production under tree crown was then used in the subsequent years to estimate the total production by ha, considering an open area of 27.6% of the total. Clumps of sporocarps were considered as a single occurrence and hypogeous sporocarps or fructifications in woody debris were not taken into account. Specimens were identified to species level in most cases and samples that could not be identified at the species level were grouped into a genus taxon. For economic evaluation, sporocarps were categorized according edibility and commercial importance.

Economic evaluation

The annual net income was estimated by the difference between the annual gross outputs and the input costs per treatment. The annual gross outputs was estimated by the production and market value of nuts (kg FW ha^{-1}), forage (kg FU ha^{-1} , being $1 \text{ FU} = 0.75 \text{ kg DM}$) and edible commercial mushrooms (kg FW ha^{-1}). The market price for nuts was estimated considering the number of nuts per kg of fresh weight, a standard parameter used to establish their market price. Annual input costs were estimated by the costs associated with each treatment: tillage, seeding, soil fertilization, pruning, irrigation, fruit and edible mushrooms harvests. Irrigation costs included the substructures (well drilling, pumps, pipes, and sprinklers) at local market prices (considering 30 years of useful life) water, yearly running energy, equipment conservation and manpower.

Statistical analysis

For nut, forage, mushroom production, fungal species richness and sporocarp occurrence, the analysis of variance ANOVA was followed, considering as source of variation the year and treatment effect and the position related to tree canopies (in case of forage production), its interaction and the error effect (site and trees by treatment and year), with the correspondent post hoc test for year and treatment effects. In both cases it was used the JMP (SAS, Institute Inc.) software and for the post hoc the Tukey HSD multiple comparison test (for a significance level $P < 0.05$).

Fungal species diversity in the different treatments was estimated using the total number of species or richness (S), the Shannon index ($H' = -\sum p_i \ln p_i$), where p_i is the proportion of individuals of the i th species (Krebs 1994). The Shannon index varies from 0 for communities with only a single taxon to high values for communities with many taxa, each with few individuals. For diversity analysis it was used the statistical ecology program PAST 1.79 (Hammer et al. 2001).

Results and discussion

Nut production and quality

Nut production and quality results are reported in Tables 3 and 4. The influence of the year as source of

variation on nut production was much higher than that of treatments (52.2 and 12.7%, respectively), and a considerable error effect was observed (32.8%) (Table 3). Regarding nut weight and size index (nut quality), the analysis of variance showed that the effect of years, as sources of variation, was also stronger (28.9 and 26.4%, respectively) than that associated with treatments (10.1 and 11.1%, respectively). Also, nut quality was affected at low extent (1.9 to 6.1%) by the interaction year \times treatment. In addition, a strong error effect on nut quality (55.7–59.0%) was observed, which can be attributed to the influence of differences on trees and site quality.

Significant differences among treatments and years on nut production (Table 4) were observed. The CT and NP treatments showed the lowest average values (18.8 and 19.6 kg tree^{-1} , respectively) and the highest values were observed in the NV and NIP (27.2 and 24.4 kg tree^{-1} , respectively). The advantage of the no-tillage system with spontaneous herbaceous vegetation when compared with the conventional system may be associated with the fact that the damage of the tree root system is avoided and organic C losses reduced (Raimundo 2003). Comparing treatments with spontaneous herbaceous vegetation (NV) with those with seeded pasture (NP), the significantly low nut production in the latter may be associated with great amounts of herbaceous vegetation (e.g., 3.2 t ha^{-1}) (Fig. 3). These results agree with previous findings by Raimundo (2003) in the same region and similar conditions; also, seeded pasture, with leguminous species may be more competitive for water resources than spontaneous species as reported by Dupraz et al. (1998).

No significant effect of irrigation was observed on nut production, which can be interpreted as a consequence of study chestnut plantations are deep-water-dependent (Martins et al. 2005, 2010) and irrigation supply only affected the top soil layer (see Table 2). However, a positive impact of soil water supply on yield and fruit quality has been demonstrated in a wide range of environmental conditions (Ferrerres and Evans 2006). For instance, studies developed under Mediterranean conditions, for almond trees (Goldhamer et al. 2006) and apricot trees (Pérez-Pastor et al. 2009), irrigating 55–85% of the potential seasonal evapotranspiration in the first study and, 25–100% in the last one, depending the

Table 3 Analysis of variance related to the effect of years and treatments on nut production, nut quality (fruit weight and size index) and forage production

Source of variation	df	Mean square	F-value	P-value	Expected variation (%)
Fruit production (kg DM tree ⁻¹)					
Year (Y)	3	632177.58	55.09	0.0001	52.2
Treatments (T)	3	162967.26	14.2	0.0001	12.7
Error (tree/Y/T)	120	11475.71			32.8
Fruit weight (g fruit ⁻¹)					
Year (Y)	3	3168.67	469.73	0.0001	28.9
Treatments (T)	3	1111.74	164.81	0.0001	10.1
Y × T	9	58.40	8.66	0.0001	1.9
Error (tree/Y/T)	3816	6.75			59.0
Fruit size index (mm)					
Year (Y)	3	913.41	150.71	0.0001	26.4
Treatments (T)	3	309.84	51.12	0.0001	11.8
Y × T	9	58.70	9.69	0.0001	6.1
Error (tree/Y/T)	936	6.06			55.7
Forage production (t DW ha ⁻¹)					
Year (Y)	2	549680.41	63.18	0.0001	37.9
Treatments (T)	2	212597.19	24.44	0.0001	21.4
Position	1	121129.31	13.92	0.0003	7.9
Error (site/Y/T/S)	96	8700.20			32.9

No significant interactions are not shown

growing season period, reported a positive effect of deficit irrigation on yield and fruit quality. In our study, the lack of positive response of yield to irrigation may be associated with the high irrigation deficit adopted by the land owners (percentage of irrigation related to the water deficit was 14–46%), which was much high regarding that followed in the abovementioned studies.

Regarding weather conditions, significant differences in nut production were observed between 2005 (9.2 kg tree⁻¹) and the other study years (2003, 2004, and 2006), which ranged from 25.5 to 27.9 kg tree⁻¹. The strong influence of weather conditions on fruit production and quality may be an effect of the annual rainfall amount and distribution. In fact, 2005 was the driest year, and the rainfall from October 2004 to September 2005 was similar to the reference evapotranspiration (Fig. 2), which may affect the replenishment of water retention capacity of deep soil layers.

Effects of treatments on fruit weight and size index followed the trend observed for nut production. The NV and NIP treatments showed the highest fruit weight (11.1 and 10.8 g fruit⁻¹, respectively) and size (27.4 and 27.1 mm, respectively), while the CT

treatment the lowest values (8.8 g fruit⁻¹ and 24.9 mm). The average number of nuts per kg was 90, 93, 105, and 114 for NV, NIP, NP, and CT treatments respectively, which was taken into account to estimate their market price. Values of fruit weight and fruit size (Table 4) were lower in 2005 (7.6 g fruit⁻¹ and 24.6 mm, respectively) than in the other study years (10.3–11.2 g fruit⁻¹ and 27.1–27.8 mm, respectively). Therefore, nut quality indexes were also dependent on treatments and the year weather conditions.

Forage production

As for nut production, the influence of the year as a source of variation was stronger (37.9%) than that associated with treatments (21.4%), while the effect of the position (beneath tree crowns or open areas) was very low (7.9%); also, a considerable error effect was found (32.9%). No effect of the interactions between treatments, years and position was found (Table 3).

Significant differences between years were observed in forage production, with higher value in 2007 (381.1 g DM m⁻²) than in 2006 and 2008

Table 4 Average values for nut production (kg FW ha⁻¹), fruit weight (g fruit⁻¹), and size index (mm), across treatments and years

Treatment	<i>n</i>	Average ± SE	Year	<i>n</i>	Average ± SE
Nut production (kg DM tree ⁻¹)					
CT	34	18.8 ± 2.1 b	2003	39	27.9 ± 1.6 a
NV	35	27.2 ± 2.1 a	2004	36	25.5 ± 1.7 a
NP	37	19.6 ± 2.0 b	2005	36	9.2 ± 1.7 b
NIP	36	24.4 ± 2.1 a	2006	31	27.8 ± 1.8 a
Fruit weight (g fruit ⁻¹)					
CT	951	8.8 ± 0.10 c	2003	961	10.3 ± 0.10 b
NV	963	11.1 ± 0.10 a	2004	720	11.5 ± 0.10 a
NP	960	9.5 ± 0.11 b	2005	1079	7.6 ± 0.09 c
NIP	958	10.8 ± 0.09 a	2006	1072	11.2 ± 0.08 a
Size index (mm)					
CT	237	24.9 ± 0.21 c	2003	336	27.1 ± 0.14 b
NV	237	27.1 ± 0.17 a	2004	252	27.8 ± 0.13 a
NP	237	26.1 ± 0.21 b	2005	360	24.6 ± 0.17 c
NIP	237	27.4 ± 0.16 a	2006	360	27.4 ± 0.16 a

Different letters in the same column, for each measurement, means the existence of significant differences between treatments or years ($P < 0.05$)

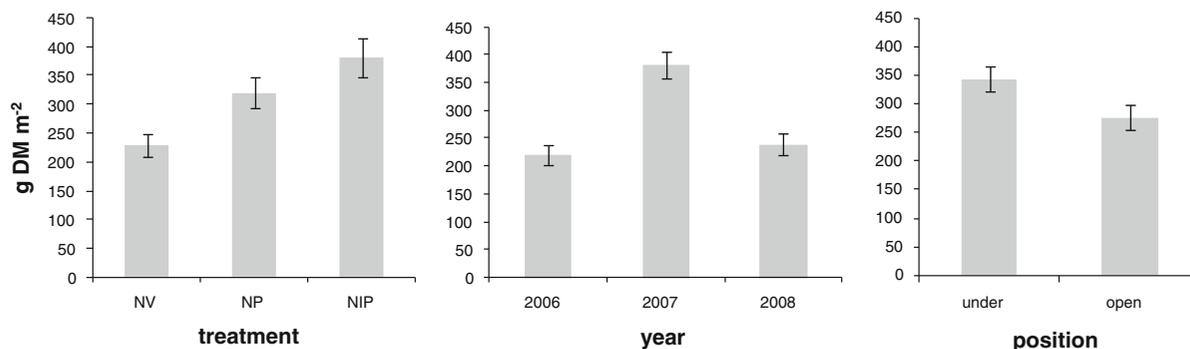


Fig. 3 Forage production (g DM m⁻²), according to treatments ($n = 36$), years ($n = 54$) and position ($n = 54$). Bars show SE

(220.4 and 238.5 g DM m⁻², respectively). Greater forage production in 2007 than in 2006 is not an effect of the annual rainfall amount (725 and 719 mm, respectively). It may be mostly associated with the rainfall amount during spring season; in fact, the rainfall during May and June was greater in 2007 (158.6 mm) than in the other study years (44.0 and 81.0 mm, respectively for 2006 and 2008; see Fig. 1 b). This trend agrees with the greater forage production (7.0 to 8.7 t DM ha⁻¹ year⁻¹) reported by Rozados-Lorenzo et al. (2007) for *Castanea sativa* plantations (58% of tree crown cover), in wetter areas with similar mean annual temperature (Galicia, Spain).

Forage production was significantly different among treatments, with the highest value in the NIP treatment and the lowest in the NV (381.0 and 228.3 g DM m⁻²), while the NP showed intermediate

values (320.1 g DM m⁻²). The lower production observed in the NV treatment, as compared with that in the NP, may be associated with the fact that spontaneous species are commonly less productive (Moreira 2007). This trend is in agreement with results of studies regarding productivity of rainfed pastures in the region of the present study (in identical climatic conditions), where the production of improved seeded pastures ranged from 2.8 to 4.2 t ha⁻¹ y⁻¹, while that of spontaneous species ranged from 1.5 to 2.4 t ha⁻¹ y⁻¹ (Moreira and Trindade 1992; Moreira 2007).

Despite of watering in the NIP treatment, differences of forage production between this treatment and the NP (381.0 and 320.1 g DM m⁻², respectively) were small, which may be ascribed to irrigation schedule. In fact, the first irrigation was

applied in middle summer (see Table 2), after the second forage sampling (late June) and therefore, during the crucial period for forage production, the NP and NIP treatments were similar regarding water availability.

A significant higher forage production was observed under tree crown than in the open (343.3 and 276.3 g DM m⁻², respectively) (Fig. 3), following results reported for other Mediterranean agroforestry systems. In fact, a similar trend was reported by Pereira et al. (2002), in the region of the present study, for pastures with spontaneous vegetation with scattered *Fraxinus angustifolia*, which was associated with the increase of soil fertility under tree crowns. Also, Moreno (2008), under stronger Mediterranean conditions, reported the same trend for the silvopastoral system of Iberian “dehesas”.

Mushroom productivity

A higher influence of the treatments as a source of variation than the year (67.7 and 13.4% respectively) was observed for total sporocarp production (Table 5). Total sporocarp biomass differed significantly among treatments, with the highest value in the NIP and the lowest in the CT treatments (151.4 and 22.5 kg FW ha⁻¹, respectively) (Fig. 4). The sporocarp productivity in the CT treatment was only 20 and 28% of that in the no-tillage system with the maintenance of natural and seeded vegetation cover, respectively.

Productivity of both total and edible-marketed mushrooms (2006–2008) is shown in Fig. 4. For economic analysis, only the most abundant marketable edible mushrooms were considered: *Boletus edulis* s.l. (*B. edulis*, *B. pinophilus*, *B. aereus* and *B. aestivalis*), *Russula cyanoxantha*, *Lepista nuda* and *Boletus fragans*. Other species found in the studied orchard are traditionally consumed and marketed but occurred sporadically, such as *Macrolepiota procera* (Scop.: Fr.) Singer and the highly prized *Cantharellus cibarius* Fr.

Significant differences were found among years, with the highest value in 2006 (122.7 kg FW ha⁻¹) and lowest and similar in 2007 and 2008 (75.1 and 83.0 kg FW ha⁻¹, respectively) (Fig. 4). This might be due to the annual variation in weather conditions, mainly in the amount of rainfall, a crucial factor for the development of the fungal fruiting bodies in the fall season (Martínez de Aragón et al. 2007). Thus, the highest productivity in 2006 can be explained by the higher rainfall than normal in the fall season of 2006 (October and November; Fig. 2b) whereas the fall seasons in 2007 and 2008 were much drier than normal.

In contrast with the total sporocarp production, the year did not show any significant effect as source of variation in the productivity of commercial edible mushrooms, while a strong effect of treatments (67.5%) and the residue (32.5%) was observed (Table 5). However, longer study periods are necessary to evaluate inter annual weather conditions, to take into account weather variability, since the

Table 5 Analysis of variance related to the effect of years and treatments on total sporocarp biomass and commercial edible mushroom production

Source of variation	df	Mean square	F-value	P-value	Expected variation (%)
Total sporocarp biomass					
Year (Y)	2	11485.47	10.95	0.0004	13.4
Treatments (T)	3	35915.78	34.24	0.0001	67.7
Y × T	6	1358.89	1.30	0.30	0
Error (trees/T/Y)	24	1048.61			18.8
Edible mushroom production					
Year (Y)	2	309.32	0.70	0.5048	0.0
Treatments (T)	3	8644.64	19.66	0.0001	67.5
Error (site/trees/T/Y)	24	439.77			32.5

No significant interactions are not shown

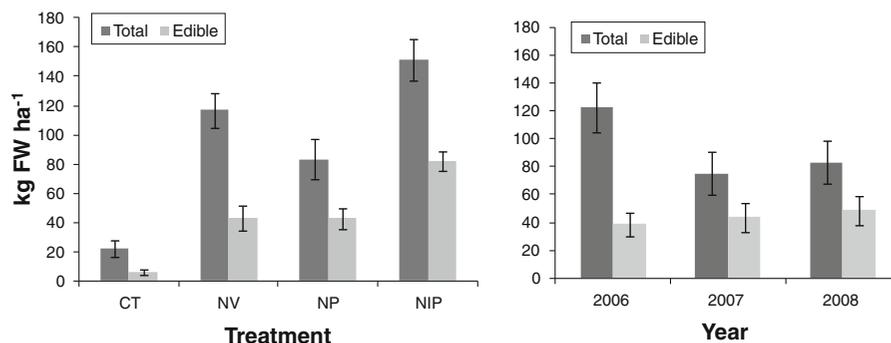


Fig. 4 Total sporocarp and commercial edible mushroom production according to treatments ($n = 9$) and years ($n = 12$). Bars show SE

observed yearly rainfall ranged only from 523 to 719 mm in the 2006–2008 period, whereas in the 2003–2008 period ranged from 459 to 1335 mm. The annual production of edible-marketed species varied from 38.6 to 48.7 kg FW ha⁻¹ (Fig. 4), which is considerably higher than productivity reported for other ecosystems, such as pine forests of Catalonia (Spain), where the production of edible-marketed species ranged from 5.3 to 22.8 kg FW ha⁻¹ (Martínez de Aragón et al. 2007).

As observed for total sporocarp production, biomass of edible mushrooms was significantly greater in the NIP (82.0 kg FW ha⁻¹) than in the NV and NP treatments (about 43.0 kg FW ha⁻¹), while that in the CT treatment (6.1 kg FW ha⁻¹) was significantly smaller than in the others. The annual fresh weight of the edible-marketed species was 54.2, 51.5, 36.9, and 27.3% of the total sporocarp production for NIP, NP, NV, and CT treatments, respectively. The highest number of commercial edible species was also collected in the NIP and the lowest in the CT treatment (average 6.0 and 3.0 species, respectively), with intermediate values in the NV and NP treatments (5.7 and 4.7 species, respectively). The greatest proportion of the edible mushroom productivity in the NIP treatment corresponded to *Boletus edulis* s.l. (average 84%), while in the NP, NV, and CT treatments the percentage was lower (67, 64, and 54%, respectively). Although *Boletus* spp. are usually abundant in forests and agroecosystems of Mediterranean regions and adapted to the intense drought during summer season by the efficiency of water assimilation (Egerton-Warburton et al. 2007; Lilleskov et al. 2009), our results suggest that their productivity can be enhanced by irrigation.

Abundance of *Boletus edulis* s.l. in the NIP treatment could partially explain the small inter annual variability of edible mushroom productivity. The observed inter annual variability on total sporocarp production, in accordance with other studies (Martínez de Aragón et al. 2007), suggests different responses of the fungal species to weather and environmental soil conditions. With the exception of *Lepista nuda*, all the other edible-marketed species are ectomycorrhizal, with an extensive fungal network on upper horizons and mineral layers (Dahlberg 2001). They can be able to access deeper water, via hydraulic lift by the host root system, being the water transferred to mycorrhizal symbionts but not to the saprotrophic soil fungi (Querejeta et al. 2003), making the last trophic group more dependent of the soil moisture. As reported by Lilleskov et al. (2009), under dryer conditions, sporocarps obtain a relative high (25–80%) portion of their water from deep or hydraulically lifted water, which maintains active the ectomycorrhizal network, even when the soil water potential is very low (Querejeta et al. 2003). Therefore, disturbance in mycelial networks caused by tillage, mainly in the driest spring seasons (in May–June), can decrease significantly the drought resistance of the plant host during the summer period.

Mushroom diversity

Over the 3-year study period a total of 67 species of fungal sporocarps and 15 taxa identified to genus were collected in the plots, of which one was found to be unique to the CT, five to NV, five to NP and eight to NIP treatments. Only 26 fungal taxa were found in all treatments. The year showed a higher influence

Table 6 Results of ANOVA tests examining the effect of years and treatments on species richness and sporocarps occurrence

Source of variation	df	Mean square	F-value	P-value	Expected variation (%)
Species richness					
Year (Y)	2	831.69	52.62	0.0001	49.9
Treatments (T)	3	458.19	28.99	0.0001	36.1
Y × T	6	25.44	1.61	0.1878	2.1
Error (trees/T/Y)	24	15.81			11.1
Sporocarps occurrence					
Year (Y)	2	12466.86	124.70	0.0001	56.9
Treatments (T)	3	5109.11	51.11	0.0001	30.7
Y × T	6	476.31	4.76	0.0025	6.9
Error (trees/T/Y)	24	99.97			5.5

Table 7 Species richness, sporocarps occurrence and Shannon index according to treatments ($n = 9$) and years ($n = 12$)

Treatment	Richness (S)	Sporocarp occurrence	Shannon index H'	year	Richness (S)	Sporocarp occurrence	Shannon index H'
CT	11.0 ± 2.3 a	20.3 ± 6.6 a	2.9 a	2006	28.7 ± 2.2 a	86.1 ± 9.8 a	3.5 a
NP	17.9 ± 3.1 b	45.0 ± 10.1 b	3.4 b	2007	12.1 ± 1.8 b	23.7 ± 4.3 b	3.1 b
NV	23.4 ± 3.1 c	58.7 ± 9.3 c	3.5 b	2008	19.1 ± 2.5 c	40.9 ± 6.5 c	3.6 a
NIP	27.4 ± 2.5 c	76.9 ± 13.7 d	3.5 b				

The values are average plus SE. Different letters in the same column means the existence of significative differences between treatments ($P < 0.05$)

both on species richness (49.9%) and sporocarp occurrence (56.9%) (Table 6) than on total sporocarp productivity (13.4%) (Table 5). As observed for sporocarp productivity, the highest average number of species per plot was observed in 2006 (28.7) while the lowest was in 2007 (12.1) (Table 7). Fungal fructification strongly depends on weather factors (rainfall, temperature and relative air humidity), and some fungal taxa or less vigorous mycelium do not fructify every year (Luoma et al. 2006; Martínez de Aragón et al. 2007).

Species richness was significantly higher in the NIP and NV (27.4 and 23.4, respectively) than in the CT treatments (11.0) (Table 7). The average number of sporocarp occurrences per plot showed a similar pattern, increasing from CT treatment (20.3) to NIP treatment (76.9), with intermediate values on NP (45.0) and NV (58.7) treatments (Table 7).

The year with lowest species richness and sporocarp occurrence (2007) also showed the lowest total diversity, based in the Shannon index (Table 7). Soil management systems significantly affected the diversity of fungal sporocarps. The Shannon diversity

index, which takes into account the sporocarp occurrence of a given species as well as number of taxa (O'Dell et al. 2004) was significantly lower in the CT than in the no-tillage treatments NV, NP and NIP (Shannon Diversity t -test; $P < 0.05$; PAST). The higher diversity of sporocarps in the NIP treatment, as also abovementioned for total productivity, can be explained by the increase in water availability in irrigated plots, given the strong influence of moisture on development of fungal fruiting bodies (Wiklund et al. 1995; O'Dell et al. 1999; Salerni and Perini 2004). The lowest diversity and abundance of fungal sporocarps in the CT treatment are expected since many soil fungi are mainly abundant in the organic layer present on the upper soil surface layers. Vegetation cover and the increase in crop residues in the no-tillage treatments (NV, NP, NIP) may provide a more heterogeneous substrate, with greater amount of organic matter, and may create more favorable microclimatic conditions (Drury et al. 1999) to support fungal metabolic activities and development of sporocarps. In contrast, in the CT treatment, soil organic matter is incorporated into the

soil and its breakdown is accelerated, as reported in a previous study in the same systems (Raimundo 2003). As most of the fungal sporocarps found in the studied orchard were ectomycorrhizal species, relying on carbohydrates provided from the host tree (Harvey et al. 1997; Dahlberg 2001), their hyphal network is highly susceptible to disturbance (Miller and Lodge 1997), which reduces the density of the fungal mycelium and the C flow, with deleterious effects on the production and diversity of sporocarps. Furthermore, the regeneration of the fine roots after the tillage is carbon-costly for the tree host and probably implies a reduction on the amount of C compounds available for fungal populations in the CT treatment.

Sporocarp data represents an incomplete view of the total soil fungal diversity because, for most of species, the relationship between the sporocarp occurrence and the distribution of the fungal mycelium belowground is unknown (Gardes and Bruns 1996; Horton and Bruns 2001). However, differences in sporocarp abundance between treatments probably reflect different mycelial abundance in the soil, as a result of the soil disturbance and modification of the microclimatic soil conditions. Further long-term research is needed to better understand the impact of disturbance induced by soil management practices on both saprotrophic fungi and mycorrhizal hyphal networks.

Results showed that conservative soil management practices, such as maintenance of a natural vegetation cover, increase the mushroom productivity and diversity, including the edible species. The present results are in accordance with studies (Frey et al. 1999; Alavalapati et al. 2004; Eichhorn et al. 2006; Regato and Salman 2008) reporting that the enrichment of the soil carbon pool by the vegetation cover, improves soil productivity and quality, through reduced erosion, higher water retention, nutrient availability and promoting fungal diversity.

Economic evaluation

The annual input costs for each treatment include the operations related to soil and system management, as reported in Table 8. The values range from 1,111 to 2,058 € ha⁻¹ year⁻¹, respectively, for the NV and NIP treatments; values for the latter are mostly associated with irrigation costs.

Taking into account the number of nuts per kg, their price was 1.00 € kg⁻¹ for the CT and NP, and 1.20 € kg⁻¹ for the NV and NIP treatments. Nut gross outputs ranged from a minimum of 2,950 and a maximum of 4,591 € ha⁻¹ year⁻¹, respectively, for the CT and NV treatments (Table 9). Gross forage outputs reached 908, 746, and 539 € ha⁻¹ year⁻¹ for the NIP, NP, and NV, respectively, while those of edible mushrooms were 729, 330, 322, and 43 € ha⁻¹ year⁻¹ in the NIP, NP, NV, and CT treatments, respectively. Therefore, total annual gross outputs in the NIP and NV (5,835 and 5,452 € ha⁻¹ year⁻¹ respectively), almost doubled that estimated for the CT treatment (2,993 € ha⁻¹ year⁻¹).

The annual net income (Table 9) was higher for the NV and NIP (4,341 and 3,777 € ha⁻¹ year⁻¹ respectively) than for the NP and CT treatments (2,701 and 1,725 € ha⁻¹ year⁻¹ respectively). However, the no-tillage system with natural vegetation may be more favourable than the irrigation treatment, based on the higher income and lower environmental costs. In fact, it reduces the threat on the scarce water resources under Mediterranean conditions, which are of utmost importance to assure sustainability of ecosystems dependent on subsoil water resources (Martins et al. 2010). Besides the positive effect on diversity, the no-tillage system, as reported by Raimundo et al. (2008), may also contribute to enhance soil organic matter status, fulfilling an important role attributed to the agroforestry systems (Schoeneberger 2009).

Table 8 Annual input costs (€ ha⁻¹ year⁻¹) for each treatment

Treatment	Tillage (€)	Seeding (€)	Fertilizers (€)	Pruning (€)	Irrigation (€)	Harvest		Total (€)
						Mushroom (€)	Nuts (€)	
CT	135	0	270	68	0	35	760	1,268
NV	0	0	213	68	0	70	760	1,111
NP	0	39	213	68	0	70	760	1,150
NIP	0	39	213	68	908	70	760	2,058

Table 9 Average values of annual gross output (€ ha⁻¹ year⁻¹), annual input costs and annual net income for the study management systems

Treatments	Gross outputs (€ ha ⁻¹ year ⁻¹)				Input costs (€ ha ⁻¹ year ⁻¹)	Net income (€ ha ⁻¹ year ⁻¹)
	Nuts	Forage	Mushrooms	Total		
CT	2.950 (€)	0 (€)	43 (€)	2,993 (€)	1,268 (€)	1,725 (€)
NV	4.591 (€)	539 (€)	322 (€)	5,452 (€)	1,111 (€)	4,341 (€)
NP	2.775 (€)	746 (€)	330 (€)	3,851 (€)	1,150 (€)	2,701 (€)
NIP	4.198 (€)	908 (€)	729 (€)	5,835 (€)	2,058 (€)	3,777 (€)

Conclusions

Wide differences on fruit production and size, forage and mushroom production and diversity, were observed for the study management systems. No-tillage systems with natural vegetation (NV) or irrigated seeded pastures (NIP) enhance fruit production and fruit quality parameters, but the latter shows higher forage production. Conservative soil management practices (NV, NP, and NIP), also significantly increase productivity of mushrooms in chestnut orchards, including edible-marketed species (with high amount of *Boletus edulis* s.l.), which is considerably higher than that reported for other ecosystems. Such systems may contribute for a sustainable management of the wild edible mushrooms increasingly collected and commercialized. Weather conditions strongly affect the system productivity, fungal species richness and sporocarp occurrence increasing the production with the amount of rainfall. The no-tillage system treatment (with spontaneous herbaceous vegetation) seems to be the most favourable management system to assure productivity and sustainability of chestnut plantations, as it lead to the highest annual net income and may contribute to reconcile productive, environmental, economic and social issues. The multifunctional management of chestnut plantations may create a sustainable land-use system, promoting economic diversification, biodiversity, and environmental quality.

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