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Management of carob tree orchards in Mediterranean ecosystems: strategies for a carbon economy implementation

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Abstract This paper offers a different framework for managing Mediterranean drought carob-tree orchard ecosystems. Two dry-farming systems were compared during two consecutive years: pure productive orchards and mixed orchards in a total of 360 mature trees distributed by 18 plots with areas of 0.55 and 0.30 ha per plot, respectively. Carob, fig, almond and olive trees compose mixed orchards. Trees of the mixed orchards were more productive than those of pure orchards. The main problem of both systems was the large variability and the low fruit production due to non-bearing trees, inducing unfavorable economic returns. Yield varied between 7.7 and 28.5 kg tree^{-1} respectively in pure and mixed orchards. In this paper we propose to use carbon sequestration calculations as an added benefit to farmers. A carbon stocking model estimation was established, based on trunk diameters of different trees. We depicted two management scenarios based on fruits production and carbon sequestration incomes: a low value scenario, using mean fruit production, and a high valuable scenario based on the hypothesis that all trees reached its potential maximum. Since under dry-farming systems fruit production irregularity is still a pendent problem, mixed orchards may offer a potential higher revenue, while maintaining higher crop diversification and whole biodiversity. C sequestration benefit, as here we purpose, may represent 125–300 % of income, respectively under low or high valuable scenario. Thus, CO_2 equivalent is a novel ecological economic incentive that may potentiate a new income for farmers while assuring carob ecosystem services.

Keywords Carbon sequestration · *Ceratonia siliqua* · Ecosystems service · Environment · Fruit production · Gross income

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Introduction

Mediterranean-type ecosystems are important hotspots of biodiversity and its flora is one of the richest in the world (Myers et al. 2000). Compared with the Atlantic, the Mediterranean landscape is less characterized by woodlands rather than by scattered trees intercropped with pastures or cereals. This type of systems, similar to savannah in Africa, is the best to explore nutrient-poor soils and rocky slopes under semi-arid climate, maintaining, simultaneously, a sustainable agriculture. Burning, cutting, coppicing, terracing, cultivating, were used by humans to redesign the original forests, obtaining a sculptured landscape with a fine balance between agricultural and pastoral activities (Blondel et al. 2010).

The mosaics of landscapes that these man-dependent ecosystems have promoted, evolved together with the rural economy along the times and give rise to spots of diversity. Trees were always present in the rural Mediterranean landscape, but dependent on the exploitation and the fertility of the soil. They could appear in scattered plantations with no irrigation and either no or minimal fertilizer addition, or just to bound the plots of irrigated crops (Ribeiro 1987). The scattered trees could form intercropped systems with cereals, pastures or other drought resistant trees. There were then two types of agriculture exploitation: the irrigated crops, such as citrus trees and horticultural crops, and the dry-farming, for cereals or other fruit trees. Cost-benefits of drought systems were ample for the rural economy. The farmers and landowners took profit of the fruits and the cereals for food or feed, and the pasture for cattle. The pruning material and other residues from shrubs or trees were used for firewood. It was a true sustainable agriculture though dependent on labour work.

During the last decade of the 20th century, the trends in European agriculture, dominated by CAP, favoured a less labour work and a more market-oriented economy. This economic liberalisation and globalisation promoted different changes but, particularly, affected the rural economy. In Iberian Peninsula, cereal plantations are almost restricted to vast areas, limited by water availability and soil fertility. However, cereals or pastures are still reminiscent in "montados", a man-made ecosystem using cork oak (*Quercus suber* L.) or holm oak (*Quercus ilex* L.) (Oliveira et al. 1994) for cork or acorn production exploitation, giving rise to important hotspots of biodiversity and ecosystem services benefits (Pinto-Correia et al. 2011).

In the slopes or inaccessible plans, farmers planted the so-called drought tree orchards, composed by a mixture of multipurpose trees, particularly olive (*Olea europeae* L.), fig (*Ficus carica* L.), almond (*Amygdalus communis* L.) and carob (*Ceratonia siliqua* L.). The trees scattered in the landscape allowing the appearance of herbaceous vegetation, blooming either in spring or autumn, creating spots of endemic species. In Portugal, they are present in the so-called "Barrocal", which is located in a Natura 2000 site in southern region (Habitats Directive Site PTCON 0049, EU), and covers about 20,000 ha of the Algarve province (total area of 5000 km^2). In this region, the sustainable traditional agriculture dominated by that mixed orchards stays giving some profit to farmers. The fruits, carobs, almonds and dry figs are easily stored without any particular care for several years and constitute valuable revenue to be used during less-productive incomes (Santos 1990). Throughout the years, these stable systems have also changed due to the development of a "part-time agriculture" rather than a valuable and profitable activity. Olive, fig and almonds were, and still are, frequently planted trees but, when abandoned, they resprout or germinate within the heterogeneous and less cared tree drought orchards.

In the second decade of 21st century, and due to economical and sociological reasons, there was a significant reduction of "Barrocal" area occupied by almond and fig trees, as well as olive trees. One of the main reasons was a consistent drop of prices of almonds in the national and regional markets and a poor investment on traditional crops as a whole. In consequence, there is a lack of interest by young farmers and growers which prefer to invest on short-term profitable crops. In this "Barrocal" region and due to abandonment, shrubs of *Pistacia lentiscus*, *Quercus coccifera* and other Mediterranean *macchia* species constitute now an extensive mosaic of distinct ecosystems that cover semi-natural areas. Independently of this abandonment, mixed orchards in "Barrocal" are still managed under dry-farming agriculture and very few cultural practices are done, such as mineral fertilization or drip-irrigation or even tillage (two times per year) to control weeds and prevent soil compaction.

Contrary to all this social and agro-system evolution, carob orchards have been increasing due to the particular ecological and agronomical traits of this crop. Carob exhibits several drought adaptation mechanisms and is highly efficient on water and nutrient use (e.g. Correia and Martins-Loução 2005). Portugal produces 35,000 Mg of fruit per year (mean of 10 years, 2000–2009) but the seed is still the most important sub-product (Martins-Loução 1990). The seed endosperm is polysaccharide (carob bean gum, CBG or locust bean gum, LBG) and the processed gum is used as a thickener, stabilizer, binder and gelling agent in the food industry. The seed embryo (germ flour) has 50 % of carob in, water-insoluble protein content with similar rheological properties to gluten (Wang et al. 2001), but due to the low level of cysteine. This protein is quite different from wheat gluten, and this property may be of major importance to search for gluten-free additives (Smith et al. 2010). Besides, the germ flour contains an interesting balance in essential amino acids according to FAO (Dakia et al. 2007) and higher contents in glutamic acid, aspartic acid and arginine (Bengoechea et al. 2008). All these characteristics increase the potential use of this Mediterranean tree plant.

Presently, most of carob orchards are conducted as either mixed or pure orchards. Tree spacing of carob multipurpose dry-farming orchards is about 10 × 10 m but with a large variability, since fig trees and almond trees are still grown in between. People's decision about orchard management in general and in particular, for adapting to market value and climate variability, are made in response to multiple forces acting at local level and dependent on the market value of the products.

Supporting and regulating ecosystem services (for a review see De Groot et al. 2002) in order to create economic and ecological interdependencies as revenue for farmers, are not properly claimed. On the other hand, data concerning the linkage between productivity under contrasting management practices, economic and C returns in Mediterranean systems is scarce. As pointed out by Vayreda et al. (2012) the assessment of C stocks at global or regional scale has received little or no attention in the semi-arid Mediterranean region and most of the studies refer to forest species.

Taking into consideration the sustainable value of carob products in the global economy and its C storage importance this strong connection between agriculture management, regional economy and ecosystem services should be addressed. In this paper we propose to show the importance of carbon sequestration as farmer profits from agriculture, as an approach to evaluate the benefits (economic and ecological) people may obtain from this type of dry-farming production system. To approach this, we focus our work on comparing two different management systems: pure orchards (>10 years old) and mixed traditional orchards (also >10 years old) to evaluate fruit production and carbon sequestration capacity. The data obtained is expected to suggest the best management practices for new farmer growers and to indicate the gross and net income per ha provided by fruit production and CO_2 credits as ecosystems services. This analysis will give information on the potential of these dry-farming system exploitations as source of complementary income in marginal regions of the Mediterranean basin and may be considered an important bridge builder between research and landscape management due to its ability to express land use trade-offs.

Materials and methods

Soil and climate

The climate is Mediterranean characterized by warm, dry summers and cool, humid winters (Mitrakos 1981, Ochoa-Hueso et al. 2011). The average annual rainfall is between 450 and 500 mm and it's mainly concentrated in winter, sometimes assuming a torrential pattern. Summer drought extends for 5–6 months, which in turn lead to frequent fires particularly in areas dominated by highly dense shrubland. These weather characteristics largely contribute to soil erosion and land degradation. The soils of the "Barrocal" region are calcareous, very rich in active lime (more than 9 % of $CaCO_3$) and with high pH (>8). Typically, they are heavy textured soils with low concentration of organic matter, low N and low P availability but with medium to high available K (Köpp et al. 1989; Correia and Martins-Loução 2004). The owners, due to multiple reasons, do not commercially explore most of the productive areas of "Barrocal" region. Besides those climatic conditions, the major factor of constraint is the small size of agricultural area per farmer (<0.5 ha in average) and it is frequent that each farmer has several small and scattered plots very apart from each other. Another constraint is the heterogeneity of production, between years and between trees within years.

Systems under study

We sampled 18 plots with an area of circa 0.2 ha each, previously chosen in a selected area of the "Barrocal" region (Fig. 1). This area is located in Loulé region, which represents 35 % of the total productive area of Algarve (INE 2011).

The plots represent two major producing systems in this province: pure orchards and mixed orchards of the same age ($\approx$ 10 years old) are described as follows:

(a) Pure orchards: 300 trees were monitored in 12 plots. These are mature, productive trees and in these plots, shrub density is controlled by permanent cutting practices followed by soil tillage. The average plot area is 0.55 ha with 45 trees per ha, as tree density. The variability is high and the distribution of the trees is irregular. For statistical purposes, each tree was considered as an independent repetition and all trees within the 12 selected plots were studied.

(b) Mixed orchards: 60 trees were monitored in a total of 6 plots (different from the ones referred in (a) but sharing the same pedo-climatic conditions, with an average plot area of 0.30 ha. Thirty-three trees per ha are distributed irregularly. These trees are also mature and productive but in these plots, carobs are mixed with other tree species, like almond, fig and olive. This pattern was not found in all plots, but at least one species was present together with carob. Only carob trees were selected for this study. As in pure orchards, each tree is a repetition, and all trees were monitored.

Within each system, trees were selected in order to assess as much variability as possible in terms of cultivars, pruning systems and intensity, weed control and soil tillage. Most of the trees (>50 %) selected to this study belong to "Mulata" and "Galhosa" cultivars, which are particularly important for seed industry in this region, and therefore the most cultivated. Regarding pruning systems, farmers do not follow a fixed protocol, but within both systems it was possible to found the following practices: (i) removal of dead wood only, (ii) regulatory pruning, and (iii) formation pruning. Weeds are mechanically removed around trees, and below canopies this operation is done by hand in order to facilitate pods harvesting. Weed control was done one or two times per year, mostly depending on climatic conditions. Distance between trees (carob only, or carob with fig, olive, almond) are similar in both systems.

Tree parameters

In all trees, height and canopy diameter were measured. The tree height was obtained from the soil surface to top of the canopy and the correspondent diameter was measured as its ground projection. Fruit production (pods) was registered in all trees of each system, and in two consecutive years (2002 and 2003).

Determination of carbon stock

Carob is a long-lived evergreen species and therefore it would be also important to evaluate the potential for carbon (C) sequestration and C stock. In order to estimate C stock (in kg) in each tree, the following model was applied:

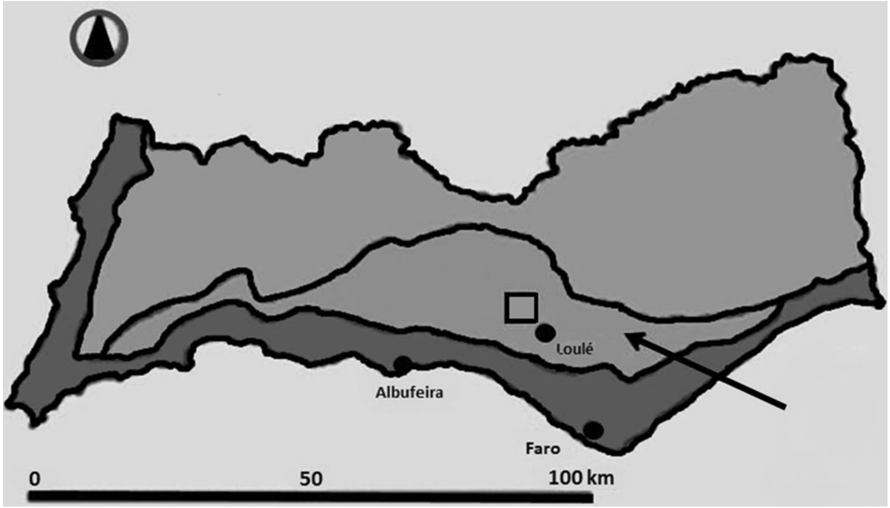

Fig. 1 Province of Algarve (southern Portugal) showing the location of the plots (*square*) within the Barrocal region (*arrow*)

$$C = 0.1884 \times Diam^2 + 1.3783 \times Diam;\ N = 8;\ R^2 = 0.98;\ F = 310.5;\ P < 0.001$$

where Diam refers to trunk diameters (in cm) measured in the field. It was not always possible to measure trunk diameter at breast height (DBH), due to the branching pattern of the trees, and in these cases, a middle point of the main trunk was chosen. The model was obtained by harvesting several trees with different ages and trunk diameters, ranging from 1 to 57 cm (the later corresponding to a tree with 8.5 m high) using an independent data set of trees in different sites of the Algarve region covering contrasting pedo-climatic conditions (Geraldo, unpublished results). The characteristics of those trees are shown in Table 1. The aboveground material (leaves, branches and main trunk) were removed and weighted and dried until constant weight. It was assumed that 50 % of dry weight is C (Brown et al. 1986; de Oliveira 1986).

Since this study refers to established orchards, installation costs were not considered. The costs for pruning, tillage and pods harvest during 2002 and 2003 were calculated based on preliminary guidelines from (Paquete 1994) and updated to current labour costs. A price of 4.07 Euros per Mg of CO_2 was used to calculate the monetary value of C sequestration (Olivier et al. 2013). In this work we considered 0.30 Euros per kg of pods, which is the value paid by commercial traders and kibblers directly to farmers in southern Portugal during 2013/2014, and 2014/2015.

Data analysis

An exploratory data analysis was performed on both systems (pure or mixed orchards). System was considered the main effect, and tree height and canopy diameter were studied by one-way ANOVA, where each single tree is a repetition, after testing for homogeneity of variances (Levene's test). Since yield values did not follow a normal distribution, a non-parametric test (Mann–Whitney U test) was used to compare means. A total of 360 trees were evaluated considering both systems. Regression analysis was used to investigate the relationships between yield and canopy diameter. Statistical analysis was done using SPSS software (version 17.0).

Results

Tree parameters, yield and plot areas of the two systems are shown in Table 2. Height (6.4 m per tree) and canopy diameters (7.3–7.8 m in average) were similar in pure and mixed orchards.

Another important outcome is the yield pattern. In 2002, fruit production was only 7.7 kg of pods per tree in pure orchards, but in some trees yield reached 70 kg. However, the median was 0.0 kg meaning that half of the sample (150 trees; 50 %) had no fruits. The pattern in 2003 was similar. Forty-one percent of trees presented no production, leading to a low mean (10.6 kg) and a low median (4.0 kg) per tree. In mixed orchards, carobs grow together with almond trees, fig trees and olive trees in a random layout, and the distance between trees is highly variable. The selected trees (60) are distributed in 6 plots with a mean area of 0.30 ha each and fruit production per tree was significantly higher comparatively to pure orchards. In 2002 and 2003, the average of fruit production was respectively 3-fold and 2.6-fold greater than in pure orchards, but again, a large variability was found. In this case, however, the medians were 17 kg and 19.5 kg respectively for 2002 and 2003. In mixed orchards, 33 % and 3 % of the trees did not produce in 2002 and 2003, respectively.

Table 1 Characteristics of carob trees used for carbon estimation model

Tree identification	Age (years)	Trunk diameter (cm)	Height (m)	Carbon (kg)
1	5–7	9.87	4.0	11.07
2	1	0.91	0.48	0.030
3	12	5.16	1.9	4.08
4	>50	56.69	8.5	674.70
5	>40	27.37	7.0	230.55
6	>10	5.4	na	3.620
7	>10	8.7	na	9.260
8	>10	2.8	na	13.540

Tree ages in cases 4–8 are a rough estimate since it is not possible to know the exact age

na not available

Table 2 Descriptive parameters of the two systems

	Pure orchards	Mixed orchards
Number of plots	12	6
Plot area (ha)[a] ± SD	0.55 ± 0.40	0.30 ± 0.07
Number of selected trees	300	60
Trees $ha^{-1(a)}$	45	33
Height (m) ± SD	6.4 ± 1.9	6.4 ± 1.8[ns]
Maximum (m)	12.9	10.4
Minimum (m)	2.6	3.0
Canopy diameter (m)	7.3 ± 2.2	7.8 ± 2.0[ns]
Maximum (m)	13.5	12.4
Minimum (m)	2.4	3.2
Yield 2002 (kg $stree^{-1}$)	7.7 ± 12.5	21.7 ± 23.8*
Median	0.0	17.0
Maximum (kg)	70	103
Minimum (kg)	0	0
Yield 2003 (kg $tree^{-1}$)	10.6 ± 15.8	28.5 ± 22.7*
Median	4.0	19.5
Maximum (kg)	98	86
Minimum (kg)	0	0

Height and canopy diameter are the average of two consecutive years, 2002 and 2003; plot area is the average of all selected plots of each system

Means with (*) significant differences between systems at $P < 0.05$ (one-way ANOVA or Mann–Whitney U test)

[a] mean; *ns* non-significant; *SD*. standard deviation

Several correlations were tested between yield and tree parameters. Significant correlations were found between yield and canopy projected diameter in both systems, pure (Fig. 2) and mixed orchards (Fig. 3).

In pure orchards, the tree canopy diameter explains 34 and 20 % of yield variation, respectively in 2002 and 2003.

In mixed orchards, exponential models were also obtained, and in 2003, the canopy explained 56 % of yield, but in this system variation was high between years. Correlations between yield and tree height in both systems were also evaluated but they were not significant. In Figs. 4 and 5, yield is distributed by classes of canopy diameters in pure and mixed orchards, respectively.

A close analysis of yield patterns according to classes of canopy diameters reveals that in mixed orchards larger trees (>10 m in canopy diameter) apparently produces more fruits than similar trees grown in pure orchards. On the other hand, in mixed

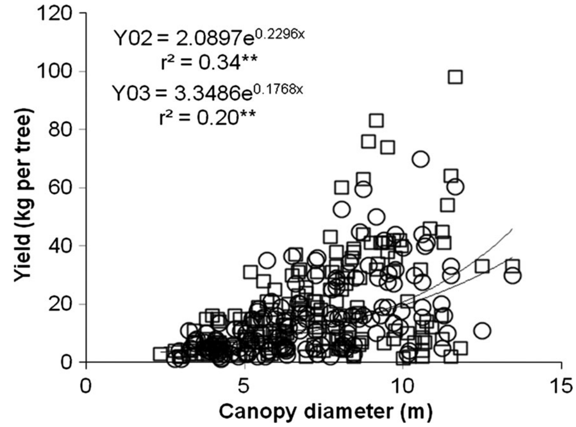

Fig. 2 Relationship between canopy diameter and fruit production per tree in pure orchards, in two consecutive years (2002, Y02, *circles*) and (2003, Y03, *squares*). Exponential models are significant at $P < 0.01$ (**)

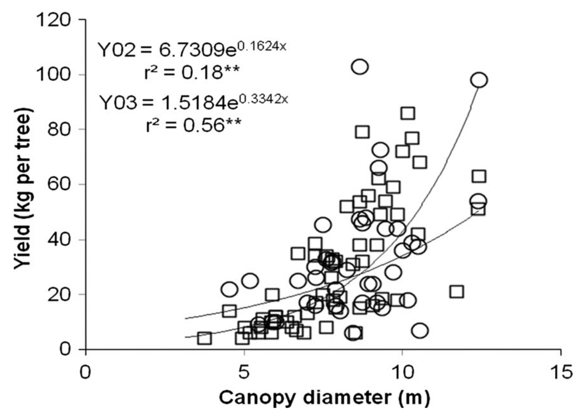

Fig. 3 Relationship between canopy diameter and fruit production per tree in mixed orchards, in two consecutive years (2002, Y02, *circles*) and (2003, Y03, *squares*). Exponential models are significant at $P < 0.01$ (**)

orchards, smaller trees are absent, at least in the plots considered in this study.

The amount of C sequestered was calculated per each tree based on a quadratic model that uses trunk diameter as the independent variable (Table 3).

In pure orchards, each trees stocked around 445 kg of C in average in the aboveground biomass (trunk, branches and leaves) and 20 Mg per ha. In mixed orchards the amount of C was slightly higher (537 kg in average) corresponding to 17.8 Mg per ha. Table 4 shows the farmer gross income for each system. The current market price of carob pods (0.30 Euros per kg in 2013) was used to calculate the income of each tree.

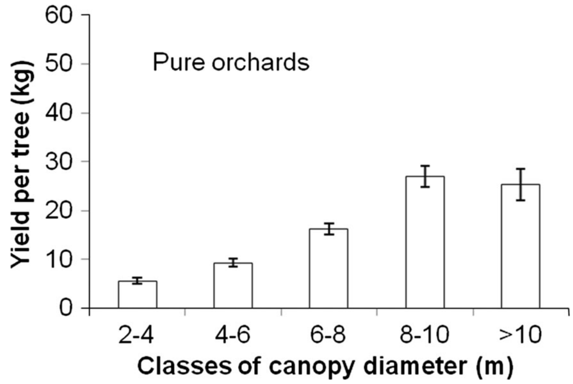

Fig. 4 Yield per tree and per different classes of canopy diameter. Mean ± SE

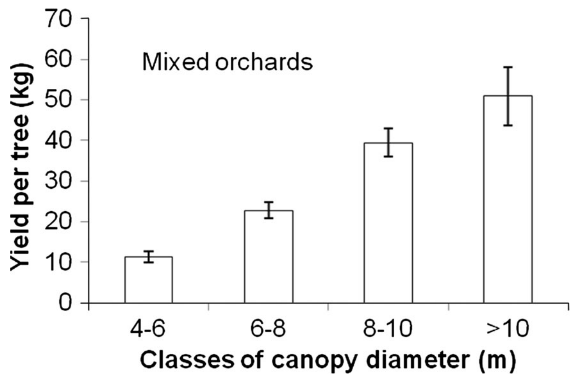

Fig. 5 Yield per tree and per different classes of canopy diameter. Mean ± SE

Table 3 Mean ([a]), maximum and minimum values of trunk diameters and carbon stocks (per tree and per ha) for each system

	Pure orchards	Mixed orchards
Trunk diameter (cm)[a]	45.1 ± 8.9	49.9 ± 8.1
Maximum (cm)	115.8	101.6
Minimum (cm)	9.8	14.1
Carbon (kg)[a]	445.7 ± 27.4	537.9 ± 23.3
Maximum (kg)	2686.2	2083.1
Minimum (kg)	31.6	57.2
per ha (Mg)	20.0	17.8
CO_2e per tree (Mg)	1.6	1.9
per ha (Mg)	74	65

Carbon values were calculated for each tree based on model (1). CO_2 equivalent (CO_2e) was calculated as C × 3.67

Extrapolation to ha should be done with some caution since the number of trees per ha in the "Barrocal" region is extremely variable. However, considering 45 trees per ha in pure orchards and for trees with more than 10 years-old (Table 2), an expected income of 104 and 144 Euros per ha should be obtained in the first and second year of results, respectively (Table 4). Hypothetically, and assuming that all trees could achieve the maximum yield (98 kg), the income would be 1323 Euros per ha. Regarding mixed orchards, an income of 215 and 284 Euros will be obtained in two consecutive years. The maximum income would be 1082 Euros per ha if all trees attained the maximum potential.

Converting to CO_2 equivalent (CO_2e), pure orchards may stock 74 Mg per ha and mixed orchards 65 Mg (Table 3). The monetary value of CO_2e in the aboveground biomass is 301 Euros and 265 Euros respectively (Table 4). In Table 5, two scenarios of land use management are depicted. The high value scenario assumes that all trees per ha attained its maximum yield (HiVS) and in consequence a maximum gross income of 1624 and 1347 Euros would be obtained in pure and mixed orchards, respectively. The percentage of added value due to CO_2e sequestration is 23 and 25 % for pure and mixed carob orchards. A "low income" scenario considers the mean of fruit production per tree (LwVS), and the gross income falls down to 405 and 480 Euros, respectively for pure and mixed orchards. However, within this scenario, the contribution of the monetary value of CO_2e sequestration increases 300 and 125 %. If maintenance costs are considered for HiVS, then the net income will be 736 and 617 Euros per ha for pure

Table 4 Gross farmer's income per tree and per ha (in Euros) obtained from fruit production and CO_2 stocks

Ecosystem services	Pure orchards		Mixed orchards	
Income (Euros)	Tree	ha	Tree	ha
From fruits: 2002	2.3	104	6.5	215
2003	3.2	144	8.6	284
Maximum (2002–2003)	29.4	1323	30.9	1082
From CO_2e stock:		301		265

Means of fruit production are those indicated in Table 1. Maximum values were chosen within the 2 years. One kg of fresh pods = 0.30 Euros; 1 Mg of CO_2e = 4.07 Euros

Table 5 Net income per ha, for each agrosystem, considering the two scenarios: HiVS and LwVS

			Costs (Euros ha^{-1})			
		Gross income (Euros ha^{-1})	Harvesting	Tillage	Pruning	Net income (Euros ha^{-1})
Pure	HiVS	1624	700	140	48	736
	LwVS	405	75	140	48	142
Mixed	HiVS	1347	550	140	40	617
	LwVS	480	150	140	40	150

The gross income included the value of CO_2e stocking

and mixed orchards respectively. The estimations for the low value scenario will be 142 and 150 Euros per ha (Table 5).

Discussion

Fruit production and land use

In spite of the large number of factors that affects yield, this work shows that in mixed orchards, the canopy diameter explained 56 % of yield variation. Since tree diameter is directly related with canopy diameter this means that larger trunks found in mixed orchards are more productive. Moreover, these trees have, in average, wider diameters than trees in pure orchards, a trait that was expressed by higher yields in both years. This trend was also observed in all classes of canopy diameters, but in particular in larger trees. Since tree densities were lower in mixed orchards when expressed per hectare the observed differences are diluted. Plot areas considered in this study are extremely low (less than 1 ha per plot), but these values are normally found all over the "Barrocal" region of the province, where the average is 1.3 ha per farm (INE 2011). It is also common that each farmer is the owner of several small plots sometimes very distant from each other, which strongly influence land management practices. These low-productive small plots are normally tilled once or two times per year and are surrounded by highly dense areas of shrubs (*Cistus* sp., *Pistacia lentiscus*, *Erica arborea*, *Phillyrea angustifolia*, *P. latifolia*, *Arbutus unedo*) and some scattered abandoned trees (*Ceratonia siliqua*, *Quercus rotundifolia* and *Olea europeae*). In some cases, these plots are conducted as intercropped systems either combining tree crops with short rotation horticultural crops or with pasture (Eichhorn et al. 2006), making the "Barrocal" a highly diversified agro-ecological system.

Another important fact was the large number of trees with no production, registered in both systems. It is possible that previous pruning may contribute to this observation but the main reason relies on the physiology of this crop. Yield irregularity and alternate bearing is a common feature of carob-tree, which can be attenuated by irrigation and fertilization (Correia and Martins-Loução 2005). However, under dry farming conditions the "on–off" pattern is frequently observed (Fig. 6) and may be attributed to multiple reasons, such as lack of pollination, fruit drop and poor fruit set, or hormonal inhibition from fruits or seeds of previous fruiting season (von Haselberg 1986).

The independent data shown in Fig. 6 may support the representativeness of the yield results obtained in this study. In years 1988, 1990, 1992 and 1994, low production per tree is mostly related with the existence of non-bearing trees within the population of 460 trees. This pattern was also registered in 2002 and 2003, which is frequently observed in southern Portugal. This is a reality that farmers must deal with, particularly in marginal soils where small cultivated carob-trees plots are found in remote locations. Although this comparison was not possible to perform for mixed orchards, we believe that the conclusions will be similar.

Apparently, in mixed orchards, the presence of other growing species in between influenced positively the production of carob. In fact, and probably due to the low carob density observed in these plots, carob was able to optimize canopy architecture according to site conditions and minimizing competition effects. In a comparative study of *Pinus sylvestris* and *Quercus pyrenaica*, (del Río and Sterba 2009) found that the volume increment per occupied area was greater in mixed stands, as opposed to pure

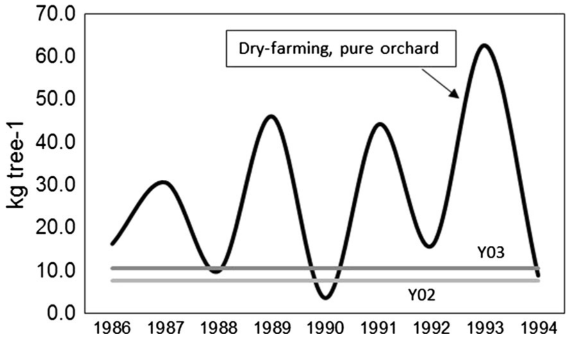

Fig. 6 Yield variation (kg tree^{-1}) observed in a 9 years' period in pure carob-tree orchard located in southern Portugal (unpublished data). This data refers to 460 mature trees distributed in four plots with the following areas, 1.7, 1.4, 0.9 and 0.3 ha, totalizing 4.3 ha. *Horizontal lines* indicate the means for fruit production in 2002 (Y02) and 2003 (Y03) for pure orchards (see Table 1)

stands, and there was a clear reduction of crown competition between species.

The question that may arise is if in mixed orchards, almond, fig and olive trees may promote carob growth (facilitation) based on the fact that farmers had conducted several ameliorative practices, like soil tillage, fertilization and application of organic amendments, in order to improve land productivity. These practices were subsequently abandoned but its long-term effects may be still effective. It is also possible that the presence of deciduous species like fig and almond tree may contribute to improve nutrient cycling as proposed by Kelty (1992). Additionally, it is also possible that the residual presence of shrubs in mixed orchards could led to an increase of soil organic carbon (SOC) and, thus, of soil fertility. In a recent comparative study, Novara et al. (2014) concluded that SOC was higher under semi natural vegetation than in permanent olive groves and this result should be taken into consideration in land-use of semi-arid regions.

In traditional forest stands, it is normally reported the increase of productivity of mixed stands compared to pure stands, normally attributed to the complementarity of the species for light and resources (Vallet and Pérot 2011; Forrester et al. 2011). Carob agrosystems as those reported in this work cannot be compared with forestry systems since in these carob orchards fruit production is the sole target and not biomass (e.g. timber) production. Fruit production is a function of multiple factors (climate, plant hormones, pollination efficiency and others) that, in this specific case, may mask the interaction between trees and soil competition effects. Carbon (C) stocks evaluation in a Mediterranean semi-arid forest ecosystem was studied by Vayreda et al. (2012) and it was concluded that structural richness (which is driven by land use, age of the trees and development stage, and management activities) was the main predictor of stand tree C stock.

Economic benefits

The gross income per ha, and assuming current market prices (0.30 Euros per kg of fresh pods), is obviously coupled with tree density, which is highly variable. In Spain, values of 50 trees per ha are reported by Tous et al. (2008) and in experimental orchards with 140 trees per ha, yield per tree ranged from 13 to 48 kg, depending on cultivar. In Portugal, tree density in productive non-irrigated orchards varies between 25 and 120 individuals. The results obtained in this study indicate greater fruit production per tree in mixed orchards, triggering higher incomes (284 Euros per ha in 2003 and assuming 33 trees per ha), because sampled trees grown in those systems have trees with larger diameters (trunks and canopies). Higher densities greatly increment yield per ha but it is possible that some competition for resources (nutrients, water and light) may limit the yield potential in a long-term perspective. Probably these systems are much more intensively managed (fertilization and tillage) than the dry-farming systems present in "Barrocal". This heterogeneity is a major constraint of carob orchards exploitation in the "Barrocal" agro-ecosystem and there is very few data on long-term experiments that covers the issue productivity versus tree density. Farmers are normally committed to preserve the trees because in the region there is a well-established network of traders and industrials which buy the pods for pulp and seed processing. However, it is also a problem for the industry to manage the raw material and establish the prices if the fruit supply is variable between years.

In chestnut plantations in northern Portugal, trees conducted under conventional tillage produce a net income of 1700 Euros per ha (Martins et al. 2011) which is much higher than the values reported for carob orchards, but we must take into account that in our study a large number of trees did not produce any fruits within the plots sampled, and that the pod market value considered in our study is low. Although the prices of carob pods are relatively constant on a long-term basis (Rita et al. 2000), in a short term

(1–3 years) the variation is high, which is a major constraint to a sustainable exploitation of the land.

Taking into considerations the problems stated above, novel alternatives should be considered in order to compensate the loss of income due to absence of fruits in a particular year or years, and carbon (C) sequestration is a viable option. The amount of C sequestered in pure orchards (20.7 Mg per ha) was slightly higher than in mixed orchards due to the higher tree density rather than due to tree size. Carob is a slow growing species and it is normally recognized that these crops may accumulate more C than the fast growing trees (Nair et al. 2009). It may be proposed that farmers would be compensated for the C they sequester, based on the market price, thus generating an important ecological service. The values of C obtained in this study are lower comparing with tropical agroforestry systems (Somarriba et al. 2013) or pine tree in Spanish Mediterranean forests (Bravo et al. 2008; Vayreda et al. 2012). These differences are coupled to tree density and if we considered the amount of C sequestered on a single tree basis, the amount in carob tree is much higher. The calculation of C stocks also in fig trees, almond trees and olives was not considered in this study but it would considerable increase the total amount of C per ha thus supporting the viability of the two systems under study: pure orchards with higher densities or mixed orchards with larger trees. The costs of integrating again almond tree and fig tree as sources of profit, needs further investigation since these species are in decline in southern Portugal. However, it should be evaluated even for a recovery of these typical Mediterranean multiple systems of dry-farming, contributing to reconcile productive, environmental, economic and social issues.

Currently, payments to farmers as revenues from C market may be implemented and cover other management costs, like for example harvesting costs and pruning practices. In Portugal, ecosystem services payments were already proposed for cork oak savannah ecosystem (Bugalho et al. 2011). As pointed out by Bryan et al. (2013), agricultural strategies in smallholder producers should consider a holistic assessment of joint strategies of policymakers, researchers and producers rather isolated approaches. Moreover, this view was also supported by a recent analysis of the concept of High Nature Value Farmland (HNVF) in southern Portugal that claims a better integration of horizontal agri-environment policies (Ribeiro et al. 2014).

Our results allow proposing two possible scenarios for land use management using carob-tree as the main crop: pure orchards may provide higher income per ha but in mixed orchards carob trees may be potentially more productive. Since low fruit production and fruit production irregularity is still a pendent problem in carob exploitation under dry-farming systems, mixed orchards may offer a potential higher revenue, while maintaining higher crop diversification and whole biodiversity. Because of the need to offer both economic and ecological incentives in agriculture, C sequestration benefit, as here we purpose, may represent 125–300 % of income. Thus, it should be taken into consideration in the support of this specific agroecosystem. Further studies should be implemented to evaluate the whole system C sequestration, which means including all the shrubs and other trees in the calculations. This could be a third scenario to take into consideration assuring the sustainability and evaluation of whole agro-ecosystem.

Conclusions

The two possible management practices must be kept in use since they offer different revenues considering low and high productive years. However, in a long term, and independently of the large irregularity in fruit production, observed either in pure or mixed orchards, mixed orchards can offer more economic and ecological incentives taking into account the full ecological benefits of biodiversity and crop diversification conservation. Also, carbon sequestration is a novel and useful economic benefit that must be considered in long-term agricultural programs. Carob-tree orchards may be compensated by carbon credits and overcame the lack of fruit production during off-years.

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