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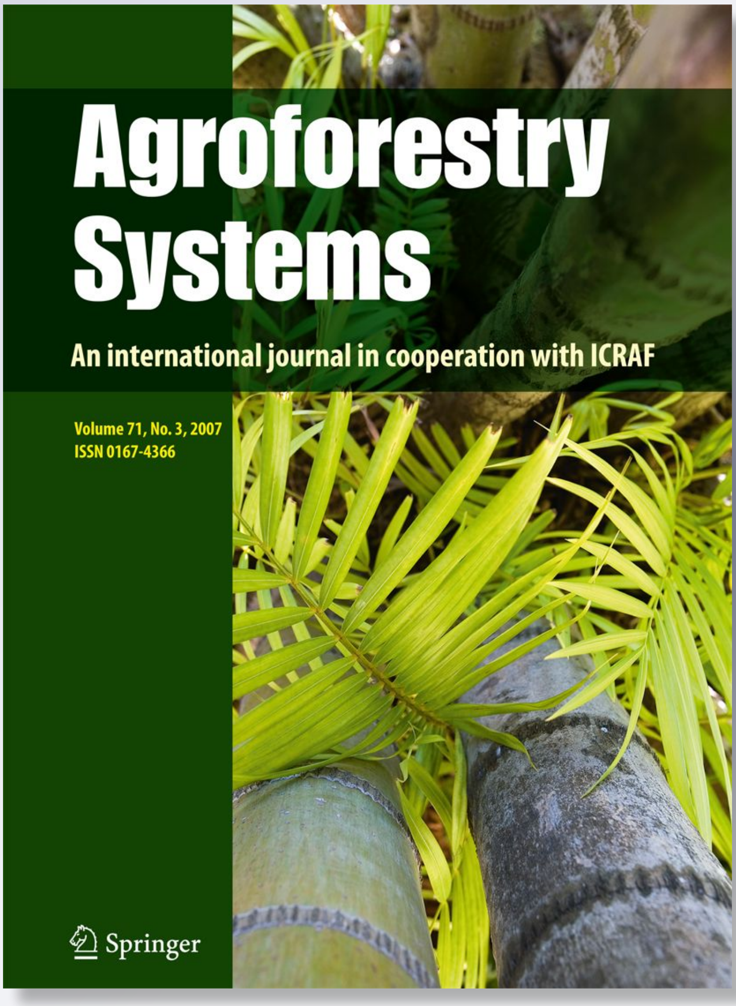

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Carbon storage in the Mediterranean upland shrub communities of Montesinho Natural Park, northeast of Portugal

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Abstract Carbon storage is one of the several important functions of shrub communities in terrestrial ecosystems and could represent an effective way to mitigate climate change. Accordingly, biomass carbon (above and belowground), litter carbon, and soil organic carbon (SOC) were studied in three shrub species: *Cistus ladanifer* (*C. ladanifer*), *Cytisus multiflorus* (*C. multiflorus*), and *Erica australis* spp. Aragonensis (*E. australis*)—representing dominant shrub communities found in Montesinho Natural Park (PNM), NE Portugal. The experimental design envisaged testing the effects of species and topography on variables mentioned and procedures carried out included assessments in areas covered by the three communities mentioned, in different topographic conditions (gentle slope, about 5 %; moderate, around 15 %; steep, around 25 %), with three replicates. Above and belowground biomass and litter were collected in 1 m2 plots, where soil samples at depths of 0–5, 5–10, and 10–20 cm were taken (disturbed for C mass concentration, undisturbed for bulk density determinations). The aboveground biomass was separated in stems, branches, branchlets, leaves, and fruits. Carbon mass concentrations determined in biomass, litter, and soil were converted to kg C m^{-2} ground area. Results showed that: (1) under the conditions studied, over 80 % of carbon is stored in the soil; (2) the contribution of biomass is higher in *E. australis*, representing about 20 % of carbon storage in the system; (3) for total carbon storage in the whole system, species followed the pattern *E. australis* (12.8 kg C m^{-2}) > *C. ladanifer* (10.5 kg C m^{-2}) ≅ *C. multiflorus* (10.5 kg C m^{-2}); (4) effects of topographic conditions were not significant in the global C storage, with 10.6, 11.6, and 11.7 kg C m^{-2} in gentle slope, moderate, and steep, respectively.

Keywords Carbon stocks · Biomass · Litter · Soil organic carbon

Introduction

During the last century, the CO_2 concentration in the atmosphere increased from 280 to 367 ppm (IPCC 2001) and the carbon cycle in terrestrial ecosystems has a recognized key role in regulating actual levels and trends in that concentration (Dixon et al. 1994; Houghton et al. 2000). Besides its scientific interest, the issue is part of international policies that committed countries with actions towards sustainable development (e.g., Kyoto protocol). In this context, reduction of atmospheric C gases results from both

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emission decrease and increased sequestration in biomass pools (IPCC 2001). As far as control and efficiency in C sequestration is concerned, agroforestry has a relevant share among those systems based on primary productivity, taken either in the ecological or in the socio-economic sense, and this is one of the significant ecosystem services agroforestry is currently providing (José 2009; Mosquera-Losada et al. 2009).

Agroforestry generally accommodates spatially distributed agricultural and forest activities, managed in an articulated way that may include common or shared practices (Nuberg et al. 2009). In rural areas, land-use and land-ownership patterns are mutually conditioned, generating spatial complexity, further increased by past and actual trends of evolution, quite evident in those affected by negative changes in land-use intensity, in the end leading to agricultural land abandonment (Cerqueira et al. 2010; Nunes 2008). This is especially the case of upland areas, traditionally with agro-silvopastoral production systems, less intensive when compared to those dominant in lowlands. Highlands are actually under pressure in what concerns farm socio-economic and territorial sustainability (Aguiar et al. 2009), and, as set-aside grows, shrub covered areas tend to increase (Kuemmerle et al. 2008). Scrubland spots are, as they have always been, an integral part of land-use systems in mountain areas, and their increased spatial relevance, nowadays coupled with the recognized ecosystems services they provide, presents a multiple-target challenge for traditional agro-ecosystems (Bompastor et al. 2009; IPB/ICN 2006).

Productive functions are assigned to shrub spots, and grazing is often an important one, mainly by sheep flocks in the Portuguese highlands. Fire prevention of planted forest tracts is often performed through prescribed fire to reduce fuel in the neighboring shrubland. As well, reduction of ignitable fuel is also achieved allowing sheep grazing in shrubland, managed by shepherds that sometimes used fire to improved vegetation quality of those extensive grazing areas. Since long, they were biomass pools where litter bed material was collected for manure, a currently declining practice, as well as that of collecting fuel for house heating. Shrubs are currently and traditionally integrated in upland production systems' management, either strictly forest-based, or mixed-farming, or even broader based agro-silvopastoral (Aguiar et al. 2009; Castro 2010; Figueiredo 2010; Lázaro and Montiel 2010; Montiel and Herrero, 2010). Furthermore, shrub covered areas provide many ecosystems services, that include soil conservation, water quality improvement, biodiversity preservation, and carbon storage, most of them with wide relevance in mountain areas, as these are also the headwaters of main river basins (Bompastor et al. 2009; Figueiredo 2010; IPB/ICN 2006; José 2009). Thus, it is important to stress that, in the interest of society; economic benefits should be provided to landowners or users for land-use and management practices that allow the maintenance of environmental services (FAO 2007).

Carbon storage in above and belowground biomass, in litter, and in mineral soil is one of the several important functions of shrub communities in terrestrial ecosystems, native or productive. These communities accumulate carbon both in biomass and in soil organic matter, except if disturbance occurs. Estimating carbon stocks and their distribution in different compartments of ecological and production systems is essential to understand the amount to which carbon is allocated to labile and stable components (Sierra et al. 2007). This information is also important to evaluate the quantity of carbon that is potentially emitted to the atmosphere when natural or human-induced disturbance occurs in those areas. Actually, the knowledge of shrub communities' effects on carbon stocks is still scarce around the world. However, shrub vegetation may require much closer attention if set-aside (meaning conversion of agricultural land use to native vegetation) is included as a carbon sink under the international policy core acts (Coomes et al. 2002; MacClaran et al. 2008).

According to Rees et al. (2005), there is a scientific obligation to improve the understanding of the processes contributing to carbon storage in terrestrial ecosystems. Soil organic carbon is the most important part of the terrestrial carbon pool and plays a crucial role in the global carbon cycle (Tang et al. 2006; Zhang et al. 2008), containing about twice as much carbon as the atmospheric CO_2 reservoir (Percival et al. 2000). It is essential, therefore, to better understand the dynamics of soil carbon (Post and Kwon 2000; Sharma and Rai 2007), and its contribution to carbon storage in systems such as shrub communities.

Shrub communities increased in area in northeast of Portugal over the last years (Aguiar et al. 1992), which is mainly explained by an increase in forest fire occurrence and by the increasing abandonment of agricultural land. For this reason shrubs, which account for about one-third of the 75,000 ha of Montesinho Natural Park (PNM), are an important component of land cover and should play a significant role in the carbon balance of this region (Castro et al. 2010; IPB/ICN 2006). The objective of this study was to quantify the biomass, litter, and soil carbon storage for three shrub species (*Cistus ladanifer, Cytisus multiflorus*, and *Erica australis spp. Aragonensis*), dominant in the PNM, NE Portugal, which are also common in Mediterranean landscapes, aimed at using this data to evaluate their contribution to regional carbon stocks.

Materials and methods

Study area

The present study was carried out in PNM, which is a protected area located in the northeast of Portugal from 41°43′47″ to 41°59′24″ N and 6°30′53″ to 7°12′9″ W, covering around 75,000 ha (Fig. 1). PNM presents a heterogeneous relief, with plateaux cut by deep valleys and some mountains, with slopes varying from flat to very steep. The altitudes range between 438 and 1,486 m asl. A large part of PNM is supra-mediterranean, annual average temperature being of 8–12 °C and annual average precipitation of 1,000–1,600-mm, concentrated from October to March (IPB/ICN 2006). Schist is the widest represented soil parent material, but basic rocks, ultramafic rocks, granites, and migmatites are lithological groups relatively important in the area.

The spatial distribution of the soil groups shows the strong dominance of Leptosols (77.1 %) followed by Cambisols (20.1 %), the well developed soils (Luvisols and Alisols) covering 2 % of the territory (Agroconsultores and Coba 1991; Figueiredo 1990). The native vegetation is *Quercus pyrenaica* but its dramatic reduction in recent centuries led to the degradation of soils that are now basically covered by shrub species (Aguiar et al. 1992). Currently the shrub communities are considered stable components of the landscape (Figueiredo 1990).

Sampling design and technique, sample treatment

Data were obtained in June 2007, the time of year that, for most species, corresponds to maximum production of biomass, either aboveground (Arevalo et al. 2009; Lufafa et al. 2008) or belowground (Curt et al. 2001). The shrub covered area surveyed is in the NE part of PNM, at 900 m elevation, where the main shrub communities can be found in a short distance range. Three sites, located on schist derived Umbric Leptosols, were selected for sampling, each covered by one of the three dominant shrub communities (*Cistus ladanifer*, *Cytisus multiflorus*, and *Erica australis spp. aragonensis*), and with variable slope gradient according to topographical position (gentle on crest, about 5 %; moderate on shoulder, around 15 %; steep on mid-slope, around 25 %). In each site, nine plots of 1 × 1 m were established along the hill-slope (three replicates per slope gradient), so as to include shrub plants between 60 and 80 cm height. The choice of such a range in plant height followed local observation which allowed considering a reference plant size for comparing the different shrub communities studied.

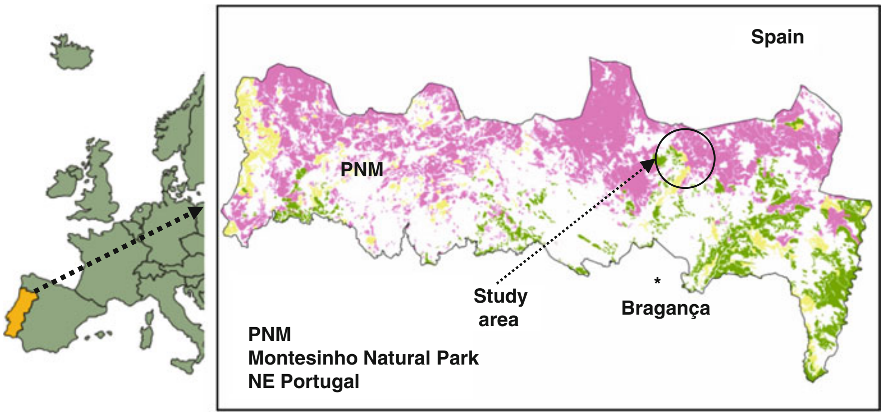

Fig. 1 Location of the study area in Montesinho Natural Park (PNM), NE Portugal (shrub cover represented by colored areas). (Color figure online)

Besides, it should be noted that the mentioned plant height accommodated requirements concerning vegetation size imposed by erosion experiments carried out in these areas with a portable rainfall simulator (Bompastor et al. 2009).

In each plot, total height and crown cover of shrubs were measured. Then shrubs were clipped and roots were excavated to evaluate biomass in the above and belowground components, respectively. Aboveground biomass was separated in fruits, leaves, branchlets, branches, and stems. Samples of fruits were collected from *C. ladanifer* ($n = 9$) and *C. multiflorus* ($n = 5$) and leaves only in *C. ladanifer* ($n = 9$), because, unlike the remaining plant components, these were not present in all plots ($n = 27$). Other components (branchlets, branches, stems, and roots) were collected from all plots ($n = 9$ each component and species). The excavation depth for sampling the belowground biomass varied with rooting species patterns. Because the soils are very shallow and stony (Umbric Leptosols of schist), the root systems were concentrated in the base of the shrubs, reaching relatively low depths rarely exceeding 50 cm. To collect the roots it was often necessary to move large quantities of stones to reach the end of some roots. The *C. multiflorus* and *C. ladanifer* species reached higher depths around 55 cm, while the *E. australis* species did not exceed 40 cm in depth. Total root biomass was determined without separation by diameter classes. Silva et al. (2003) refer in similar soils (Lithossols of schist) located in the Central East Region of Portugal (Serra da Malcata) the maximum rooting deep of 35 and 60 cm for species *Erica australis* and *Cytisus multiflorus*, respectively. Root:shoot ratio was computed, for each plot, with the amount of C in below ground biomass and that of total above ground biomass.

The litter was defined as organic material deposited over mineral soil and entirely collected, after measuring thickness in five points randomly selected over plot ground. Biomass and litter samples were dried at 65 °C for 72 h to determine dry mass. Total soil organic C down to 20 cm depth in the plots was calculated from C concentrations in soil cores collected in the 0–5, 5–10, and 10–20 cm soil layers and from soil bulk density at the same depths. Because the soils are very shallow and stony, soil sampling was only possible in these depths. Bulk density was determined in undisturbed samples, weighting oven-dried soil (at 105 °C), collected in 100 cm^3 cylinders. Samples for soil C were air dried and sieved to determine the coarse fraction (>2-mm).

All samples of biomass components, litter, and mineral soil were analyzed for total C by dry combustion (ISO 1994). Soil samples were tested with an acid-drop but no carbonates were detected, thus the total soil C was assumed to be comparable to soil organic C. Biomass and litter mass values were converted to carbon (expressed in kg C m^{-2}, given the size of the area sampled) multiplying these values by the C concentration in dry matter. Soil organic carbon (C_{SOC}, kg C m^{-2}) was calculated multiplying C concentration(C_c, g kg^{-1}) by bulk density (BD, g cm^{-3}) and thickness (z, cm) of the mineral soil layer with a correction for coarse elements content (CE, v v^{-1}) using the following equation (Percival et al. 2000; Tate et al. 1997):

$$\mathrm{C_{SOC}} = z\mathrm{C}(\mathrm{BD} - 2.65\ \mathrm{CE}/100)$$

The total carbon storage (TC) per unit area (kg C m^{-2}) was estimated by summing the mean amount of carbon in different pools:

$$\mathrm{TC} = \mathrm{C_{AB}} + \mathrm{C_L} + \mathrm{C_{SOC}}$$

where C_{AB} is carbon content in above and belowground biomass, C_{L} is carbon content in litter, and C_{SOC} is carbon content in soil.

Statistical analysis

Two-way ANOVA tested the effects of Species and Topography (with 2 degrees of freedom assigned to each one of these factors and 4 to their interaction) on each variable assessed, except in the case explained below. Following ANOVA, Turkey tests allowed statistical comparison of variable means at $P < 0.05$ level for the significant experimental design factors and interactions (Steel and Torrie 1980).

In what concerns carbon in plant biomass, differences were hypothesized between plant components in their C concentration and C contents. In these cases, the two-way ANOVA comprised the effects of species and components, and their interaction (the latter with 4 degrees of freedom), as there is no sound experimental basis to state topography as a factor conditioning C concentration and C contents in plant biomass.

Correlation and linear regression, simple and multiple, were also part in the statistical analysis of data. Analyses were performed using 11.5 version of the SPSS software.

Results

C in above and belowground biomass

C concentration

Carbon concentration in biomass was significantly affected by the factors under test, namely plant species and components, and their interaction (Fig. 2). Average values range from 55.3 % in *C. ladanifer* to 56.3 % in *E. australis*, a 1 % difference that is statistically significant. Differences higher than these occurred between average C concentrations in the biomass components. Lowest C concentration was found in roots (53.6 %) and highest in stems (57.0 %). Branchlets and branches, with a similar mean (56.1 %), are the only components, which values do not show statistically significant differences. This general pattern was actually followed by *C. multiflorus* but, for *C. ladanifer* and *E. australis*, differences between components were all statistically significant. The low data scatter, as indicated by a global CV as low as 3 % about a general average of 55.8 % C concentration in biomass, may explain the results of statistical tests. In spite of these, data highlight the narrow range of C concentration found in biomass in these ecosystems, as 80 % of data fall within a range of 3.5 % C, and 90 % of data fall within a range of 4.9 % C. This data consistency may seemingly be assigned to species and component specificity.

C storage

For *C. multiflorus* and *E. australis* approximately 75 % of the aboveground C was stored in stems and branchlets together, this latter component representing the largest fraction (41 and 46 % for *C. multiflorus* and *E. australis*, respectively). For both components, the *E. australis* C storage was significantly higher when compared to the other species. In *C. ladanifer*, stems account for 41 % of all C accumulated in the aboveground biomass, the leaves 30 %, and, unlike other species, branchlets represent less than 6 % (Fig. 3). Total biomass C storage varied significantly with respect to shrub species and non-significantly with slope (Fig. 4). The amounts of belowground C ranged between 0.17 (*C. multiflorus*) and 2.36 kg C m^{-2} (*E. australis*) and of aboveground ranged between 0.46 and 0.80 kg C m^{-2} for the same species. *E. australis* had the largest global biomass C stock (above and belowground), significantly different from the other two species (Table 1). For this species, the belowground fraction is 1.71 kg C m^{-2}, meaning 71 % of total biomass C stock, whereas other species have much lower proportions. On the contrary, a relatively smaller C amount (0.69 kg C m^{-2}) is found in *E. australis* aboveground fractions, when compared to the other species (Table 1; Fig. 4).

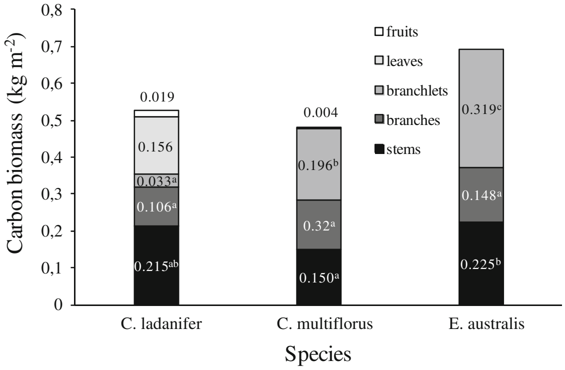

Fig. 3 Carbon in aboveground biomass components (kg C m^{-2}): means for each species. Average values of each biomass component with the same letter are not significantly different ($P > 0.05$)

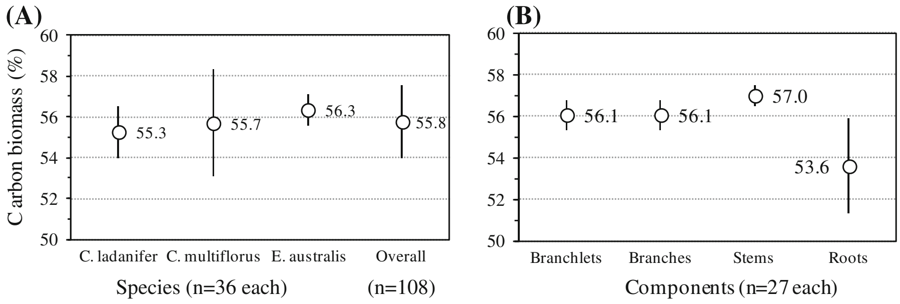

Fig. 2 Carbon concentration in biomass (%): mean ± standard deviation for plant species (**a**) and components (**b**). For each one of these variables, averages followed by the same letter are not significantly different ($P > 0.05$)

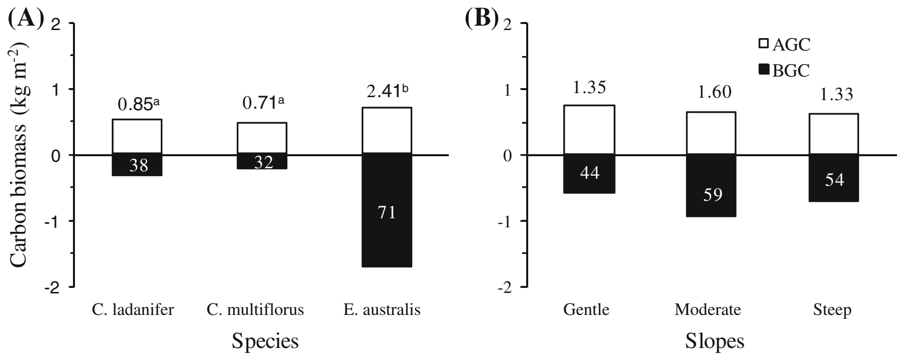

Fig. 4 Carbon in above (AGC) and belowground (BGC) biomass (kg C m^{-2}) in relation to species (**a**) and slope (**b**). *Numbers above bars* indicate total C in biomass; numbers *inside bars* indicate percentage C in belowground biomass. For species or slope, averages with the same letter are not significantly different ($P > 0.05$)

The root:shoot ratio mean values were significantly affected by both shrub species and slope, the highest value being calculated for *C. multiflorus* (2.09) and the lowest for *E. australis* (0.40) (Table 1).

Aboveground biomass (AGB) shows a significant correlation with crown cover (CC) and total height (TH) of shrubs, considered together in multiple regression analysis:

$$\mathrm{AGB} = -411.343 + 6.904\,\mathrm{TH} + 15.181\,\mathrm{CC}\left(r^2 = 0.382,\ P < 0.003\right)$$

Table 1 Average above and belowground carbon storage (kg C m^{-2}) and root:shoot ratio in relation to slope and species. For species or slope, overall means of each variable with the same letter are not significantly different ($P > 0.05$)

Slope	Species			Overall
	C. ladanifer	*C. multiflorus*	*E. australis*	
Aboveground C storage (kg m^{-2})				
Gentle	0.57	0.51	0.80	0.63
Moderate	0.52	0.48	0.67	0.56
Steep	0.50	0.46	0.60	0.52
Overall	0.53^{a}	0.48^{a}	0.69^{b}	
Belowground C storage (kg m^{-2})				
Gentle	0.42	0.29	1.08	0.60
Moderate	0.21	0.23	1.69	0.71
Steep	0.32	0.17	2.36	0.95
Overall	0.32^{a}	0.23^{a}	1.71^{b}	
Root:shoot ratio				
Gentle	0.74	0.57	1.35	0.95
Moderate	0.40	0.48	2.52	1.70
Steep	0.64	0.37	3.93	1.37
Overall	0.60^{a}	0.48^{a}	2.48^{b}	

Litter C storage

C. ladanifer shows the highest C concentration in litter (50 %), followed by *C. multiflorus* (47 %), and by *E. australis* (38 %).

Litter carbon storage and litter layer thickness in the *C. ladanifer* were significantly higher than those of other shrub species. Carbon accumulation in the litter was similar in all slopes, but the thickness was significantly lower in gentle and steep slope gradients (Table 2). The litter layer was very thin (0.12–2.50 cm), with the lowest values in *E. australis* and in steep slope.

A strong positive correlation was observed between litter C storage (LCS) and litter layer thickness (LT), and this may be helpful for litter C storage estimates, based on a much simpler to assess parameter as litter thickness. The regression equation is:

$$\mathrm{LCS} = 0.1229\,\mathrm{LT} + 0.0437 \quad \left(r^2 = 0.81, P < 0.000\right)$$

Soil C storage

Organic C concentrations in soils decreased with increasing depth in all shrub species and slopes, showing values generally over 50 g C kg^{-1} of soil (Table 3). The concentration of soil organic carbon (SOC) in the first 5 cm ranged from 68.6 g kg^{-1} (*C. ladanifer*) to 81.0 g kg^{-1} (*E. australis*) and reveals significant differences between them.

The 0–20 cm soil profile contained an average of 9.5, 9.6, and 10.3 kg C m^{-2} in the *C. ladanifer*, *C. multiflorus*, and *E. australis*, respectively (Fig. 5). In this study, bulk density differed significantly

Table 2 Litter carbon storage (kg C m^{-2}) and litter layer thickness (cm) in relation to slope ($n = 9$ each slope) and species ($n = 9$ each specie), expressed as mean and standard deviation. For species or slope overall means with the same letter across columns and rows are not significantly different ($P < 0.05$)

Slope	Species			Overall
	C. ladanifer	*C. multiflorus*	*E. australis*	
Litter C storage (kg m^{-2})				
Gentle	0.28 ± 0.08	0.13 ± 0.03	0.10 ± 0.09	0.17 ± 0.10
Moderate	0.34 ± 0.07	0.10 ± 0.11	0.07 ± 0.01	0.17 ± 0.14
Steep	0.22 ± 0.06	0.11 ± 0.07	0.02 ± 0.01	0.12 ± 0.9
Overall	0.28 ± 0.08^{b}	0.12 ± 0.07^{a}	0.06 ± 0.05^{a}	
Thickness of litter layer (cm)				
Gentle	1.67 ± 0.76	0.67 ± 0.29	0.38 ± 0.33	0.91 ± 0.69^{ab}
Moderate	2.50 ± 0.50	0.75 ± 0.25	0.23 ± 0.06	1.16 ± 1.01^{b}
Steep	1.50 ± 0.50	0.28 ± 0.19	0.12 ± 0.03	0.63 ± 0.67^{a}
Overall	1.89 ± 0.66^{b}	0.57 ± 0.29^{a}	0.24 ± 0.19^{a}	

Table 3 Carbon concentrations (g C kg^{-1}), mineral soil bulk density (g cm^{-3}) and coarse elements percentage in the three layers of mineral soil according to slope ($n = 9$ each slope and layer) and species ($n = 9$ each specie and layer), expressed as mean and standard deviation. For species or slope, averages with the same letter among rows are not significantly different ($P < 0.05$)

Depth (cm)	Species			Slope		
	C. ladanifer	*C. multiflorus*	*E. australis*	Gentle	Moderate	Steep
SOC concentrations (g kg^{-1})						
0–5	68.6 ± 11.8^{a}	69.5 ± 17.6^{a}	81.0 ± 7.3^{b}	66.3 ± 11.4	70.8 ± 15.2	76.2 ± 22.6
5–10	59.2 ± 8.5	61.1 ± 10.6	69.6 ± 4.8	56.3 ± 9.6	67.2 ± 7.8	66.4 ± 6.2
10–20	45.9 ± 6.5	50.6 ± 8.4	56.8 ± 7.0	45.6 ± 4.6	56.0 ± 7.0	51.7 ± 9.9
Bulk density (g cm^{-3})						
0–5	1.18 ± 0.10^{a}	1.15 ± 0.15^{ab}	1.09 ± 0.14^{b}	1.24 ± 0.13^{a}	1.08 ± 0.12)^{b}	1.10 ± 0.09^{b}
5–10	1.25 ± 0.09	1.24 ± 0.10	1.20 ± 0.13	1.24 ± 0.09	1.26 ± 0.09)	1.19 ± 0.14
10–20	1.37 ± 0.11^{a}	1.32 ± 0.10^{a}	1.21 ± 0.13^{b}	1.35 ± 0.15^{a}	1.24 ± 0.09)^{b}	1.30 ± 0.11^{ab}
Coarse elements content (%)						
0–5	42.8 ± 7.1	47.4 ± 5.4	49.0 ± 6.3	45.5 ± 7.0	48.5 ± 6.5	45.2 ± 6.5
5–10	49.0 ± 6.7	54.1 ± 6.8	53.2 ± 6.1	49.4 ± 5.9	53.4 ± 6.4	53.4 ± 7.6
10–20	52.3 ± 5.0	50.7 ± 6.5	54.1 ± 5.5	51.6 ± 7.6	50.9 ± 3.3	54.6 ± 5.2

between shrub species and slopes at the top layer (0–5 cm) and the 10–20 cm layer (Table 3). Bulk density (BD) shows a strong correlation with soil C concentration (Cc) and can be estimated by the equation:

$$\mathrm{BD} = 0.0744\,\mathrm{Cc} + 1.6867\left(r^2 = 0.924, P < 0.000\right)$$

For all shrub species the SOC in 0–5 cm depth was lower in gentle slopes. There was more data scatter in 0–5 cm (CV of 20.5 %) than that of other soil layers (CV of 16.2 and 14.0 % at the 5–10 and 10–20 cm depth, respectively). SOC down to 10 cm depth represented 54.8 % (*C. multiflorus*), 57.0 % (*E. australis*), and 58.2 % (*C. ladanifer*) of the SOC stock for the whole 0–20 cm soil depth sampled (Fig. 5).

Total C storage

Total carbon storage in *E. australis* was 12.8 kg C m^{-2} which was significantly higher than the storage in *C. ladanifer* (10.7 kg C m^{-2}) and *C. multiflorus* (10.5 kg C m^{-2}) (Fig. 6). The topographical position (slope) had no significant effect on the global carbon storage. The majority of the carbon was located in the soil (*E. australis*, 80.7 %;

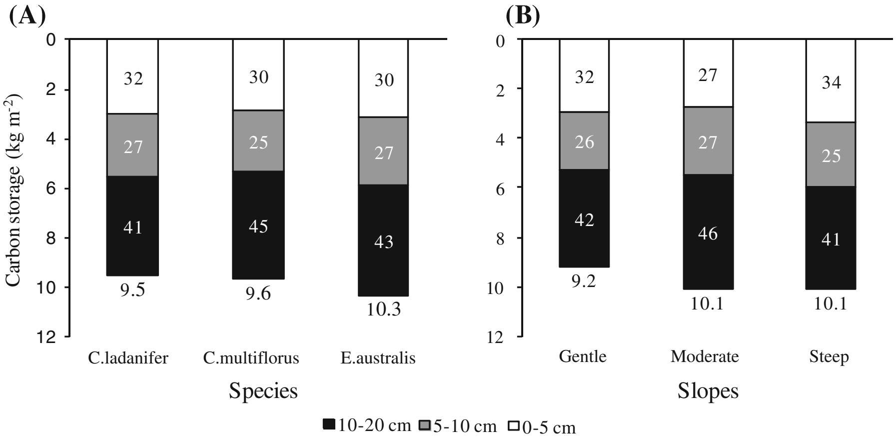

Fig. 5 Total soil organic carbon storage (*numbers below bars* in kg C m^{-2}) according to species (**a**) and slope (**b**). *Numbers inside bars* indicate percentage C in each soil layer

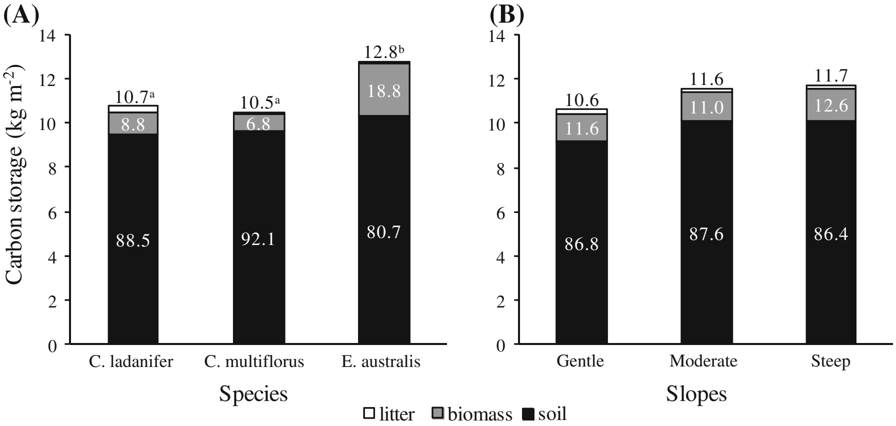

Fig. 6 Total carbon storage in the whole system (*numbers above bars* in kg C m^{-2}) according to species (**a**) and slopes (**b**) (*numbers inside bars* indicate percentage C in each compartment). For species or slope, averages with the same letter are not significantly different ($P > 0.05$)

C. ladanifer, 88.5 %; and *C. multiflorus*, 92.1 %), and for the living biomass (above and belowground) the species ranked inversely, with values of 18.8 (*E. australis*), 8.8, and 6.8 % (*C. multiflorus*). The litter accounted for only 0.5, 1.1, and 2.6 % for *E. australis*, *C. multiflorus*, and *C. ladanifer*, respectively.

Discussion

This study quantified the C pools of above and belowground biomass, litter and soil in a Mediterranean shrubland in NE Portugal. The knowledge about C storage in different components of shrub communities could give indication the potential for CO_2 release to atmosphere in case these systems suffer human disturbances or fire occurs (Bing et al. 2006; Perez-Quezada et al. 2011; Yimer et al. 2006; Zheng et al. 2008). Average values of C concentration in aboveground biomass components and roots range from 57.0 % in stems to 53.6 % in roots. These values are clearly higher than the 50 % C concentration in biomass normally assumed in C estimates (Arevalo et al. 2009; Cerrilo and Oyonarte 2006; Goetz and Prince 1998; Gower et al. 1997; Madeira et al. 2002; Nair 2011; Ordóñez et al. 2008; Pinno and Bélanger 2008). Results obtained rise awareness to the relevant errors that may occur in estimates of C biomass contents, or C balances, when applying that 50 % average. Based on data obtained in this study it is proposed, for these species, average values of 56 % C in aboveground biomass and 54 % in belowground biomass. Accordingly, when determining the amount of C stored in aboveground biomass based on C concentration measured in samples of biomass and the proposals in this paper (56 and 54 % is above belowground and biomass, respectively) the differences do not exceed 2 % for all components. However, when it admits a C concentration 50 % in the biomass, C storage values decrease about 12 % in aboveground biomass and from 3 (*C. multiflorus*) to 10 % (*E. australis*) in belowground biomass. Hence, results advise the use of more specific values according to ecosystem and plant component.

While statistical analysis did not outcome significant differences in C stored between different topographical position (slope), differences were significant between species in what concerns C stored in either biomass, litter, or soil. Above and belowground biomass C stock and mineral soil until 5 cm of depth were significantly higher for *E. australis*. It seems that the quantity and quality of biomass produced by the different species are the main cause of the differences found among the shrub communities.

Shrub species have various adaptive mechanisms to survive in Mediterranean climate (Keeley 1998; Mooney and Dunn 1970). One of these mechanisms involves a larger allocation of plant resources to root than to shoot fraction (Guilherme et al. 1998; Jurado and Westoby 1992; Lloret et al. 1999), which is possibly an adaptation to the summer water deficit (Hilbert and Canadell 1995). In this study, *E. australis* species follows this trend with root:shoot ratio that ranged between 1.35 and 3.93, but the other species (*C. ladanifer* and *C. multiflorus*) show values lower than 1. It is common to find root:shoot ratios higher than 1 in arid and semi-arid regions (e.g., Fan et al. 2008; Noy-Meir 1973;). The low root:shoot ratio values observed in *C. ladanifer* and *C. multiflorus* species suggest that the relative production of roots and shoots is controlled by species-specific development patterns (Gedroc et al. 1996). The present study helps supporting such statement, as all sampling areas were selected within a range of less than 1 km, under similar soil and climate conditions. Ratios lower than 1 are also reported for semiarid regions of Australia (Fan et al. 2008), Mediterranean arid shrubland in Chile (Perez-Quezada et al. 2011), and California chaparral (Kummerow et al. 1977). The knowledge of root:shoot ratio may be important to estimate the carbon stocks in above and belowground biomass (Ordóñez et al. 2008), particularly in the case of shrub communities, because of data scarcity concerning this type of vegetation cover. It is clear from results obtained that estimates should be species oriented and not rely in general averages.

The C storage capacity of aboveground biomass ranged from 4.6 Mg C ha^{-1} (*C. multiflorus*) to 5.0 Mg C ha^{-1} (*C. ladanifer*) and to 8.0 Mg C ha^{-1} (*E. australis*), whereas of belowground biomass ranged between 1.7, 2.1 and 23.6 Mg C ha^{-1} for the same species, respectively. Cerrilo and Oyonarte (2006) reported similar values of aboveground biomass for *C. ladanifer* (4.9 Mg C ha^{-1}) and slightly lower for *Erica sp.* (5.7 Mg C ha^{-1}) in shrubland ecosystems of southern Spain. As expected these values are high compared to the values obtained by Perez-Quezada et al. (2011) in a Mediterranean arid shrubland in Chile (0.06–3.35 Mg ha^{-1} of aboveground and 0.02–0.55 Mg ha^{-1} of belowground biomass for *F. thurifera* and *A. saligna* species, respectively). Among the different components of aboveground biomass, the largest contribution came from branchlets and stems in *C. multiflorus* and *E. australis*. In *C. ladanifer*, stems and leaves were the most important components for aboveground C storage. However, stems and branches together represent 54–61 % of C in aboveground biomass in the three species, providing a relevant C stock in vegetation, stable either under regular or accidental conditions, as those of fire occurrence, when the less lignified components are selectively burned. Aboveground biomass showed a significant correlation with crown cover and total height of shrubs ($r^2 = 0.38$). Despite the low value of r^2, this information is still relevant to the region because this is the first tool available to estimate shrub aboveground biomass in PNM area.

Litter C storage varied from 0.6 (*E. australis*) to 2.8 Mg ha^{-1} (*C. ladanifer*), and increased with litter C concentration and thickness. A strong positive correlation was found between litter C storage and litter thickness ($r^2 = 0.81$). The smallest litter accumulation under *E. australis* can be associated with higher biological degradation rates, confirmed by the lower C concentration, 38 versus 47 (*C. multiflorus*) and 50 % (*C. ladanifer*) (Bing et al. 2006; Klein et al. 2008) and can explain the higher SOC under this species. This is in accordance with the work developed by Vargas et al. (2006) who reported for a microcosm decomposition experiment, using two evergreen shrubs (*Atriplex lampa* and *Junellia seriphioides*), the decrease in litter C associated with a significant increase in SOC. Similar concentrations of carbon in litter were reported by Alegre et al. (2004) for *Colutea arborescens* (44 %) and *Medicago Strasseri* (41 %) in cold semiarid Mediterranean conditions (Madrid, Spain). Thus, in permanently vegetated soils, the effects of plant species on ecosystem are related to the quantity and quality of litter deposited on soil surface (Alegre et al. 2004; Chojnacky and Milton, 2008; Nicolini and Topp 2005). Despite its minor contribution to total carbon, litter is an important component of the carbon biogeochemical cycle (Ordóñez et al. 2008; Zhang et al. 2007), as it is the interface between vegetation and soil. Such specific location makes it a buffer zone, developed as the balance between time-lagged fluxes, namely incoming C materials from above ground vegetation layers and out coming C in organic structures at several stages of decomposition that, in turn, are a relevant input to the soil organic C pool.

The soil was the largest C pool representing until 20 cm of depth 95, 96, and 103 Mg ha^{-1} for *C. ladanifer, C. multiflorus*, and *E. australis*, respectively. These amounts of C stored in soil reflect the contribution of several influences, primarily identified with differences in biomass production by cover vegetation, for which species ranked as in soil, meaning *C. ladanifer* and *C. multiflorus* < *E. australis*. On the other hand, for organic residues accumulation on ground surface, species ranked as *C. ladanifer* and *C. multiflorus* > *E. australis*, seemingly meaning more efficient transfer of organic C from litter to soil in the latter case. Both influences are, in turn, associated with soil physical and biological conditions, and organic matter decomposition rates, that may locally prevail under the three shrub species studied, and that is also reported in literature (Madeira et al. 2002; Martins et al. 2007; Martins et al. 2009; Post and Kwon, 2000; Yimer et al. 2006; Zheng et al. 2008). These soil organic C amounts are higher than those reported by other authors in 20 cm of soil depth. Perez-Quezada et al. (2011) referred 18.7 Mg C ha^{-1} in a Mediterranean arid shrubland (Chile) and Bonino (2006) referred 22.9 Mg C ha^{-1} in shrubby grassland under a pronounced dry season (Argentina).

However, compared with other ecosystems, SOC storage is relatively lower than that found by Fernández-Núñez et al. (2010) until 25 cm of depth in silvopastoral systems one decade after established with *P. radiata* (130.7 Mg C ha^{-1}) and *Betula alba* (143.4 Mg C ha^{-1}) in NW Spain, where vegetation strata complexity and biomass production are also much higher than that found in the PNM shrubs studied, due to either vegetation type or to climatic conditions that favor biomass vegetation growth. Nunes et al. (2010) reported for first 30 cm of soils developed under *P. pinaster* in NW Portugal values that ranged from 90.2 to 123.9 Mg C ha^{-1}. As found in other studies (Grigal and Berguson 1998; Martins et al. 2007; Percival et al. 2000; Post and Kwon 2000; Zheng et al. 2008), a large number of soil organic compounds are intimately associated with mineral soil particles, and the turnover rate of SOC compounds varies due to the quality and distribution of organic inputs and soil organo-mineral interactions, both influencing the most important variations in soil carbon stocks and soil physical properties, as it is the case of bulk density (Don et al. 2007; Gifford and Roderick 2003; Ordóñez et al. 2008).

In fact, for low SOC, bulk density is not visibly affected by C concentration in soil and, therefore, soil C storage depends mainly on C concentration, meaning a positive relationship between these two variables; however, for high SOC, bulk density is visibly and negatively affected by C concentration in soil, meaning that the increase in C concentration may not be enough to compensate that decrease in the solid mass per unit bulk volume occurring when SOC is very high.

Total C storage is a sum of contributions from the system compartments and so, it directly relates to vegetation cover (above and belowground biomass), litter accumulated on soil surface and soil organic carbon. However, soil is the final destination for most of the C fixed by photosynthesis in terrestrial ecosystems, thus being an important sink of atmospheric CO_2 (Lal 2004). Results show that, among those systems, shrub communities may have a relevant role to play on this issue, as part of agroforestry landscapes of the Mediterranean mountain areas.

Conclusions

The average C concentration of aboveground (56 %) and belowground biomass (54 %) is significantly higher than the value of 50 % frequently used for C estimates, and therefore it seems necessary to limit the generalized application of that value. The C concentration in litter produced under *E. australis* is lower (38 %) than other species (50 and 47 % for *C. ladanifer* and *C. multiflorus*, respectively), meaning that the decomposition rate is higher under the former species, with positive effects on SOC. Soil carbon storage in the topsoil (0–20 cm) is similar in all species, but tends to be higher in soil under *E. australis*.

Total C storage in the whole system is significantly higher for *E. australis* (12.8 kg C m^{-2}) followed by *C. ladanifer* (10.7 kg C m^{-2}) and *C. multiflorus* (10.5 kg C m^{-2}). More than 80 % of C is stored in the soil, the biomass contribution being quite variable with species, and litter representing less than 3 %, in all species. Based on these results it is concluded that shrub communities are important terrestrial carbon pools. More attention should then be paid to these systems due to their relevant role as terrestrial carbon stocks.

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