

Soil carbon storage as influenced by tree cover in the Dehesa cork oak silvopasture of central-western Spain

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Received 25th January 2011, Accepted 3rd May 2011

DOI: 10.1039/c1em10059a

The extent of carbon (C) stored in soils depends on a number of factors including soil characteristics, climatic and other environmental conditions, and management practices. Such information, however, is lacking for silvopastoral systems in Spain. This study quantified the amounts of soil C stored at various depths (0–25, 25–50, 50–75, and 75–100 cm) under a Dehesa cork oak (*Quercus suber* L.) silvopasture at varying distances (2, 5, and 15 m) to trees. Soil C in the whole soil and three soil fractions (<53, 53–250, and 250–2000 μm) was determined. Results showed soil depth to be a significant factor in soil C stocks in all soil particle sizes. Distance to tree was a significant factor determining soil C stocks in the whole soil and the 250–2000 μm soil fraction. To 1 m depth, mean total C storage at 2, 5, and 15 m from cork oak was 50.2, 37, and 26.5 Mg ha^{-1} , respectively. Taking into account proportions of land surface area containing these C stocks at varying distances to trees to 1 m depth, with a tree density of 35 stems ha^{-1} , estimated landscape soil C is 29.9 Mg ha^{-1} . Greater soil C stocks directly underneath the tree canopy suggest that maintaining or increasing tree cover, where lost from disease or management, may increase long term storage of soil C in Mediterranean silvopastoral systems. The results also demonstrate the use of soil aggregate characteristics as better indicators of soil C sequestration potential and thus a tool for environmental monitoring.

Introduction

An increasing body of knowledge that has emerged recently shows that incorporation of trees into monoculture agriculture systems, such as occurs with the implementation of agroforestry (AF) practices, improves sequestration of carbon (C) in above ground biomass and in the soil.^{1–10} Haile *et al.*¹ found 33% greater C storage in soils near trees in a slash pine (*Pinus elliottii* Engelm.) and bahiagrass (*Paspalum notatum* Flüggé) silvopasture compared to treeless bahiagrass pastures, on Spodosols in Florida, USA. Takimoto *et al.*^{5,8} also found greater C storage in soils underlying improved tree-based practices such as live fencing and fodder bank agroforestry than in unimproved systems in the West African Sahel region of Mali. While tree-based AF systems have higher C stock in the above ground

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Environmental impact

As a signatory to the Kyoto protocol, Spain seeks to limit emissions of greenhouse gases. The role that soils play, as a source or sink for atmospheric carbon (C), is not well documented, yet critical to national accounting. This work describes how C is preferentially sequestered in the soil by trees in the Dehesa oak silvopasture of Spain, which occupy ~3 million ha in Iberia. Soil C was preferentially stored closer to individual trees in deeper soil horizons in soil fractions that promote long term sequestration. Degradation of this land use system, through disease and poor management, threatens to reduce secondary environmental benefits, such as soil C storage. The results presented here provide incentives for conservation.

biomass as compared with treeless pastures,³ there is also evidence that C storage in deep soil horizons is greater in a number of AF systems.^{1,4,5,7–10,11}

Carbon inputs to the soil from root decay, leaf fall, and animal excreta are broken down by macro- and micro-fauna. Most of this C is lost in this process of decay, but some residual C becomes incorporated into the soil, humified, and eventually it ends up in longer term soil C pools. Over time, these resistant C pools can become quite large.¹² Several studies have proposed that long term storage of C can occur in soil aggregates,^{13–16} and specifically within microaggregates and silt + clay aggregates formed within macroaggregates. The mean residence time (MRT) for soil organic C varies as a function of aggregate size class.^{17,18} Carbon associated with macroaggregate (250–2000 μm), microaggregate (53–250 μm), and silt + clay (<53 μm) size soil fractions can have mean MRT of 1–10, 25, and 100–1000 years, respectively.^{17,19}

The shift from till to no-till land use practices leads to the preferential formation of macroaggregates, which are made up by microaggregates and smaller silt-clay sized aggregates.^{15,20} This hierarchical organization of smaller sized aggregates within larger aggregates protects C stored in each occluded size fraction from microbial attack.^{6,14,20} A loss of C generally occurs where tillage is implemented on previously untilled soils,²¹ as tillage disrupts the process of macroaggregate formation, increasing bioavailable sources of C from smaller aggregates.²¹ The physical fractionation of soils into size class fractions allows us to consider the effect different land use practices have on the process of soil aggregation, how much C is contained in each fraction, and an estimation of residence times of SOC in a given soil.²⁰ In particular, the formation of macroaggregates, and thus the formation of stable microaggregates within, is affected by land management (tillage, afforestation, etc.), which is an indicator of potential long term storage of SOC.²¹

As a signatory to the Kyoto protocol, Spain seeks to limit emissions of greenhouse gases (GHG), especially carbon dioxide (CO_2). Accurate accounting of soil C sequestration will enable Spain to determine if soils are a source or sink for atmospheric C. Current land use and vegetation types in Spain, including forests and agricultural lands, are major indicators of stored C.¹² The Dehesa oak silvopasture system (*Quercus ilex* L. and *Quercus suber* L., among other *Quercus* sp.) is one of the most extant agroforestry systems in the world, occupying some 2.3 million ha in Spain and 0.7 million ha in southern Portugal.²² In the past few decades, the degradation of the Dehesa system by land use change, lack of tree regeneration, and disease (particularly, a root pathogen, *Phytophthora cinnamomi* Ronds) has threatened to undermine the potential secondary environmental benefits provided by these systems,^{23–26} which are just coming to light.^{22,27} Determining the C storage capacity of this expansive land use in Spain will be vital to national C accounting, and may serve to foment the restoration of this and other savanna-like systems in the world.

The extent of C stored or sequestered in soils depends on a number of factors including biological system characteristics, climatic and other environmental conditions, and management practices.²⁸ Since C cycling in soils is a long term process, the effect of soil properties on a specific system, and *vice versa*, may not be clear in a short time span. Therefore, an indication of

a soil's current C status as obtained from determinations of the soil C content—which is the basis for most soil C sequestration studies—alone is inadequate to describe the long term C sequestration potential (CSP) of the soil and the impact of the land-use system (LUS) it supports on the soil's CSP. Thus, it is prudent to examine if any of the soil characteristics that have a major influence on C storage in soils (physical, biological and chemical) could be used as indicators of the soil's CSP under specified conditions. Aggregate- and size-fractions of soils that can easily be measured are known to have an important effect on C retention in soils.^{18,29,30} Recent studies summarized by Nair *et al.*⁸ have shown that the amount of C stored at different soil depths varies considerably among soils depending on depth-wise distribution of aggregates. Soil C stock is also reported to be influenced by the distance from trees (less C in soils away from trees as opposed to near the trees: Takimoto *et al.*,⁵ Moreno and Obrador-Olán³¹) and tree density (more C in soils under trees with higher tree-stand density compared with those with lower stand density: Saha *et al.*⁴). Gathering accurate information on the variations in C stock across LUS and the soils that support them is also important for correcting the prevailing error of using a single value (or a narrow set of values) for C storage under a LUS such as AF in planning and development of documents at various (local/regional/national/global) levels regardless of the variability that exists among such systems and their soils. This study was undertaken to: (1) quantify and compare the amount of C stored in the whole soil and three differently sized soil fractions at increasing distances from individual cork oak (*Quercus suber* L.) trees and in four soil depths up to 1 m (0–25, 25–50, 50–75, and 75–100 cm), and (2) provide a summary estimate of the SOC storage to 1 m depth in the cork oak Dehesa at the St Esteban farm in Extremadura in central-western Spain.

Materials and methods

Study site

The study was carried out at the St Esteban Dehesa, a 120 ha working farm located about 5 km southeast of the town of Plasencia, in the Extremadura region of Spain (39°59'11" N, 6° 6'15" W); 400 m a.s.l.; mean rainfall 520 mm y^{-1} ; mean annual temperature 16.1 °C, with a monthly range of 7.9 °C in January and 25.8 °C in July). Most of the precipitation falls between October and April, and climate is considered Mediterranean, with long, hot and dry summers and mild wet winters. Soils are acidic (Table 1), identified as Luvisols according to the FAO classification system and Alfisols according to the USDA system.

Table 1 Soil pH, bulk density and texture at four depths at the St Esteban farm, Extremadura, Spain

Soil parameter	Soil depth/cm			
	0–25	25–50	50–75	75–100
pH (0.1 M KCl)	4.1	3.7	4.0	4.1
Bulk density/ g cm^{-3}	1.30	1.35	1.35	1.35
Sand/ g kg^{-1}	270	180	230	360
Silt/ g kg^{-1}	590	600	560	450
Clay/ g kg^{-1}	140	220	210	190

Soil texture is silt loam with an organic horizon to ~20 cm and an argillic horizon below 25 cm, with a range of bulk density from 1.30 to 1.35 g cm⁻¹ (Table 1). Soil depth to bedrock was in some sampling points was less than 100 cm. No accumulations of inorganic C occur in these acidic soils. St Esteban is a Dehesa oak silvopastoral system (mix of *Quercus ilex* and *Q. suber*) established at least 80 years ago, with pork, beef, and cork production as management goals. In the sampling area, cork oak was the dominant tree species at a density (estimated from aerial photographs) of about 35 stems ha⁻¹, with an unimproved native pasture in the understory. The mean diameter at breast height (DBH) of randomly selected trees, measured at 1.3 m above ground, was 58.2 cm, with a range of 48.8 to 70.1 cm and a standard error of 3.7 cm.

Experimental design

Six individual cork oak trees were randomly selected at the farm for soil sampling at three points along a transect at 2, 5, and 15 m from each tree, the distances representing points directly underneath the tree canopy, at the drip line (edge of canopy), and at three times the distance from the drip line, respectively. Drip lines for trees were similar due to standardizing pruning practices. Soil sampling was completed along a transect moving west (270°) from individual trees, as to reduce the effect of aspect on soil edaphic factors.²⁷ Soil samples were collected in January 2008 using a stainless steel cylinder with a cutting edge that was inserted with a powered hammer and removed with a platform-stabilized pulley.³² Soil cores were collected to 1 m, measured for depth, and divided in the field into four subsamples corresponding to sampling depth classes of 0–25, 25–50, 50–75, and 75–100 cm. Bulk density was determined for each sampling depth using a cylinder of a known volume.

Bulk soil samples from the field were air dried at room temperature (20–25 °C) to a constant weight, and passed through a 2 mm sieve (#10 U.S. Standard Testing Sieve). The portion of soil that did not pass the 2 mm sieve was separated, dried overnight at 70 °C (with the weight noted), and then discarded. The weight of the discarded fraction would be used to convert the eventual data derived from 2 mm sieved fraction back to field conditions.^{12,18} The <2 mm soil particle size samples are referred to as the whole soil, hereafter. Particle size analysis was completed on a subsample of whole soil using the pipette method (Soil Survey Staff, 2004).³³ Soil pH was measured for the whole soil in 0.1 M KCl at a soil to solution ratio of 1 : 2 using a Crison pH meter at 20 °C (Crison Corporation, Barcelona, Spain).

Subsamples of the whole soil were physically fractionated according to Elliott³⁴ and Six *et al.*¹⁵ A 25 g sample of 2 mm sieved air dried soil (of known moisture content) was placed in a 250 mL beaker. Distilled water (~150 mL), enough to completely cover the soil, was poured into the beaker to promote slaking. The slaking process breaks up water unstable aggregates in the soil, leaving water stable aggregates for further analysis. After 5 minutes, slaked soil was poured on top of the 250 µm sieve (#60 U.S. Standard Testing Sieve). The soil solution was wet-sieved manually by moving the sieve up and down about 5 cm each, 50 times in two minutes. What did not pass the 250 µm sieve was backwashed, with a distilled water-filled wash bottle, into a pre-weighed and numbered aluminium plate. The

remaining soil solution was next poured over the 53 µm sieve (#270 U.S. Standard Testing Sieve), and the above-described procedure was repeated. The three soil fractions, 250–2000 µm, 53–250 µm, and <53 µm, were dried at 60 °C, weighed, ground for homogenization, and stored in individually sealed and labeled plastic bags for C analysis. The fractionated soil samples are hereafter referred to as soil fractions. The whole soil, not treated with the slaking or fractionation procedure, was dried and ground for homogenization. Samples of known moisture content were then analyzed by a LECO C.N.H.S. Elemental Analyzer (Model CHNS-932, LECO Corporation, St Joseph, Michigan, USA) for percentage C within two weeks after whole soil was air dried. To ensure accurate results, the analyzer was calibrated using standards of a known C concentration, and determinations of C content for 5% of samples were repeated.

Data for statistical analysis were stored and organized using Microsoft Excel and analyses of variance for treatment factors were completed using SAS statistical software version 9.2 for windows (SAS Corporation, Cary, NC). The soil carbon concentration in the whole soil and in soil fractions, expressed in g C kg⁻¹ soil, was calculated from the percentage of carbon from the elemental analyzer using the following formula:

$$\left(\frac{\text{g C}}{\text{g whole soil or fraction}}\right) \times \left(\frac{\text{g whole soil}}{\text{g bulk soil}}\right) \times \left(\frac{10^3 \text{ g bulk soil}}{1 \text{ kg bulk soil}}\right) \times \left(\frac{\text{g fraction soil}}{\text{g whole soil}}\right)^* = \text{g C kg}^{-1} \text{ soil} \quad (1)$$

*this final term is only required to calculate g C kg⁻¹ in the fractionated soil.

The mean bulk density of the soil measured at each sampling depth was used to convert C percentages in the whole soil and fractions to Mg C per hectare (to a specified depth, *e.g.* 25 cm) basis using the following formula:

$$\left(\frac{\text{g C}}{\text{g whole soil or fraction}}\right) \times \left(\frac{\text{g whole soil}}{\text{g bulk soil}}\right) \times \left(\frac{\text{g bulk soil}}{\text{cm}^3}\right) \times \left(\frac{25 \text{ cm}}{1}\right) \times 100 \times \left(\frac{\text{g fraction soil}}{\text{g whole soil}}\right)^* = \text{Mg C ha}^{-1} \quad (2)$$

*this final term is only required to calculate Mg C ha⁻¹ in the fractionated soil.

In order to calculate the amount of C in soil fractions found in field conditions, two conversion factors are required: (1) the conversion of soil fraction to whole soil, and (2) the conversion of whole soil to bulk soil. For the whole soil, only the later conversion is needed. Mean C storage in the whole soil and soil fractions (in Mg C ha⁻¹ and g C kg⁻¹), and the percentage fraction recovery from wet sieving were compared using SAS ANOVA proc glm for linear models. Data were log transformed to meet normality requirements for ANOVA. Means reported here were converted from log-transformed data.

An ANOVA was carried out for soil depth and distance to tree treatment factors. Carbon storage in the whole soil and soil fractions at each sampling depth was compared across distances from cork trees. In order to calculate whole field storage (to 1 m) mean soil carbon storage for all summed depths to 1 m was also compared for each soil fraction and distance to tree.

Additionally, an estimate of mean soil C to 1 m for the entire St Esteban farm was calculated using C storage estimated from proportions of soil containing estimated amounts of soil C. Mean separation was completed using the Duncan-Waller multiple range test, with $\alpha < 0.05$.

Results and discussion

Depth was a significant factor affecting C storage in all soil fractions examined (Table 2). In the whole soil and the largest soil fraction, 250–2000 μm (macroaggregate size), distance to tree was a significant indicator of C storage (Fig. 1 and 2). In the smaller soil fractions, 53–250 μm , and <53 μm , distance was not significant. The interaction of depth and distance to tree was not significant.

By sampling depth, several significant differences in mean C storage were identified in the whole soil and soil fractions. In the 0–25 cm sampling depth, C storage in the whole soil and macroaggregate fraction (250–2000 μm) was 52 and 68% greater, respectively, underneath *versus* away from the tree canopy, but similar between the canopy edge and the other distances, 2 m > 15 m, 2 = 5 m, and 5 m = 15 m (Fig. 1). At 50–75 cm, the macroaggregate-associated C storage followed a similar pattern as in the 0–25 cm depth, 2 m > 15 m, 2 = 5 m, and 5 m = 15 m (Fig. 1). At 75–100 cm sampling depth, macroaggregate soil C storage beneath and at the canopy edge was greater than away from the tree, 2 m > 15 m, 2 = 5 m, and 5 m > 15 m (Fig. 1). No differences were found between distance to tree for the whole soil and soil fractions in the 25–50 cm depth.

Differences in mean C storage between the whole soil and soil fractions were found within sampling depths and distance to tree. In the 0–25 and 25–50 cm depths, C storage in the whole soil and 250–2000 μm soil fraction was similar. Below, in the 50–75 and 75–100 depths, whole soil mostly exceeded all soil fractions (Fig. 1).

Summing C storage for all soil depths (0–100 cm), significant differences were identified only in the 250–2000 μm soil fraction, with 67 and 49% more C underneath and at the edge of the canopy, respectively, as found away from the tree, 2 m = 5 m > 15 m (Fig. 3). An estimate for the whole field soil C storage to 1 m depth, 29.9 Mg C ha⁻¹, was calculated from the proportion of land containing these various total carbon stocks. The 120 ha St Esteban farm, assuming a uniform tree stocking rate and similar soil forming factors, contains an estimated 3.6 Gg of soil C stored to 1 m depth.

Table 2 ANOVA table for depth, distance, and depth by distance treatment factors for the whole soil and three soil fractions (2000–250, 250–53 and <53 μm) at the Cork Oak (*Quercus suber*) silvopasture, at the St Esteban farm, Extremadura, Spain^a

Treatment factor	Degrees of freedom	<i>p</i> -values, soil fraction/ μm			
		Whole soil	2000–250	250–53	<53
Soil depth	3	0.02	<0.001	<0.001	<0.001
Distance to tree	2	<0.001	<0.001	NS	NS
Distance to tree × Soil depth	6	NS	NS	NS	NS

^a NS is non-significant at $p > 0.05$.

Carbon storage in soil fractions

Analysis of the soil fractions (250–2000, 53–250, and <53 μm) showed that most C was stored in the 250–2000 μm (macroaggregate) fraction at all depths examined (Fig. 1). Higher C storage in this fraction is generally attributed to greater C inputs, and the preferential stabilization of organic matter (OM) in macroaggregates as opposed to smaller size class aggregates. Fraction recovery percentages (by weight) also reflect the greater macroaggregation that took place under the tree canopy in the 0–25 cm depth (Fig. 1 and 2). While greater mass recovery of macroaggregate soil fractions leads to significantly greater C storage in this fraction, the same relationship was not found in the silt + clay aggregate size (<53 μm). Macroaggregates have greater C per mass and greater mass recovery from fractionation will lead to greater C storage. Alternatively, greater mass recovery of the silt + clay fraction does not lead to greater C storage, as this fraction has less C by mass.²¹

Several studies demonstrate that protection of C within the macroaggregate size class (250–2000 μm) is affected by afforestation and cessation of tillage, represented in this study as distances closer to cork oak trees.^{35–37} Macroaggregates are held together by the biological activity surrounding fresh soil organic matter (SOM), consisting of plant residues that still have a recognizable cell structure and are referred to as coarse intra-aggregate particulate organic matter, iPOM.³⁸ Soil aggregates are often formed by microbial activity centered around coarse iPOM.^{39,40} In the process of breaking down iPOM, microbes deposit polysaccharides and other chemicals that act as binding agents in the soil. These binding agents hold mineral particles and microaggregates together, giving structural integrity to the macroaggregate. In addition, roots and hyphae grow around the iPOM, further physically protecting and stabilizing the macroaggregate.³⁹ Tisdale and Oades⁴¹ found greater concentrations of organic C in macroaggregates than in microaggregates and suggested that the presence of decomposing roots and hyphae within macroaggregates not only increased C concentrations but also contributed to their stabilization. In the process of C sequestration, the formation of microaggregates (<250 μm), where the oldest and most recalcitrant SOC is found, hinges on the formation and stability of macroaggregates and the availability of fresh SOM.⁴²

At 2 and 5 m from the tree, cork oak inputs from above and below ground led to greater C storage in this macroaggregate fraction in the 0–25 cm depth. In lower sampling depths, greater macroaggregate C was stored in the 50–100 cm depths (Fig. 1), reflecting the inputs from tree roots. Kurz-Besson *et al.*⁴³ and Aronson *et al.*²⁷ estimated that cork oak roots proliferate in this zone, and as such, this represents soil depths where root turnover, over decades of growth, has contributed greater C protected within macroaggregates. While macroaggregates in this size class have relatively short turnover times compared to smaller aggregates, the addition of organic matter to the soil at this depth would provide for the formation of stable micro- and silt + clay sized aggregates. As deeper soil horizons are less influenced by management activities, inputs of C to this depth by roots are a source of C for macroaggregate formation and preservation of C for long term in smaller microaggregate and silt + clay sized aggregates.^{21,44} Differences in soil C between

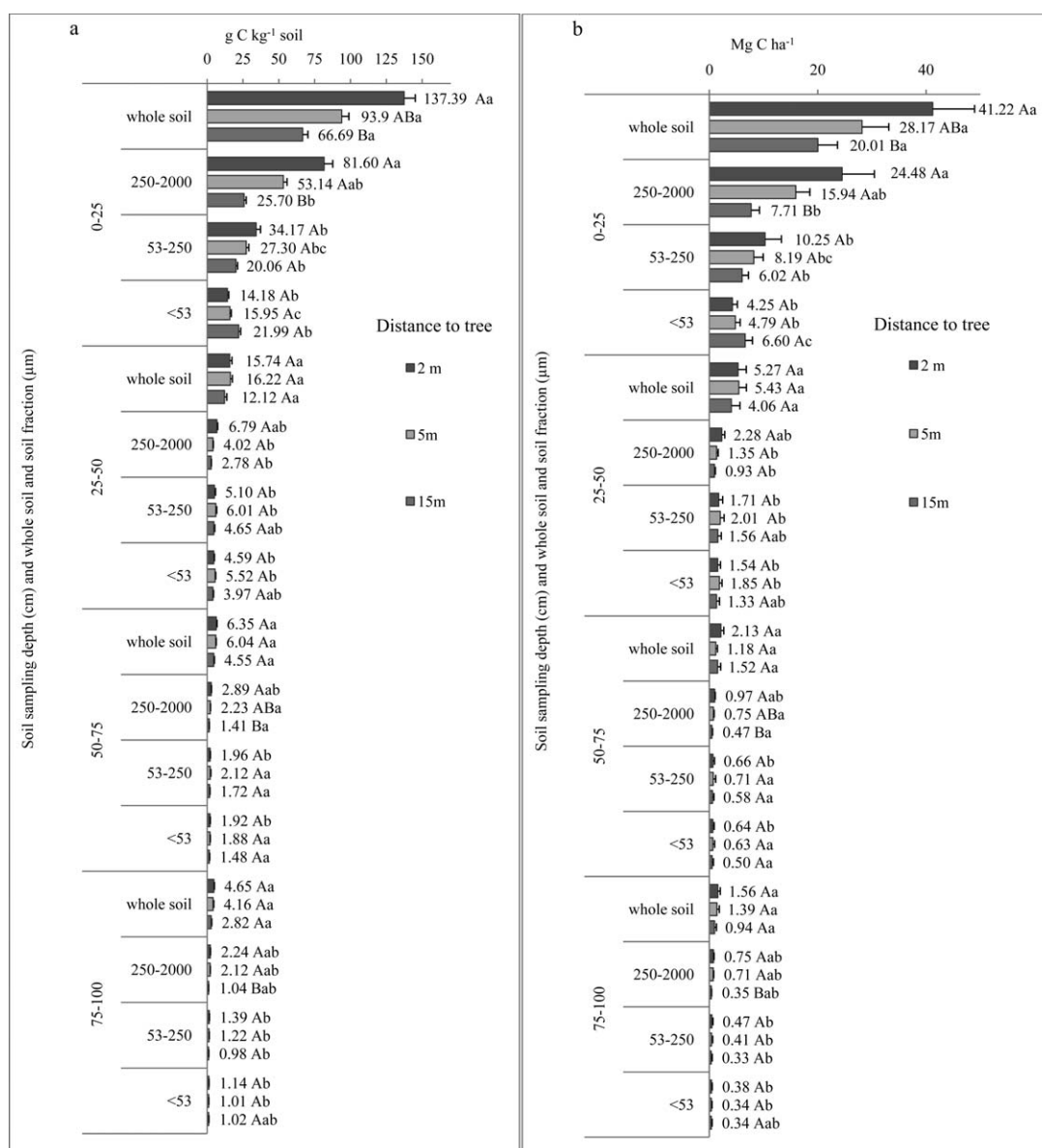


Fig. 1 Mean soil C concentration (a) in g C kg soil^{-1} and C storage in (b) Mg C ha^{-1} in the whole soil and three soil fractions (250–2000 μm , 53–250 μm , and $<53 \mu\text{m}$) at four soil depths (0–25, 25–50, 50–75, and 75–100 cm) at three distances (2, 5, and 15 m) from individual cork oak trees (*Quercus suber*) at the St Esteban farm, Extremadura, Spain. *Means followed by different uppercase letters differ among distances to tree within whole soil, soil fraction and sampling depth at $p < 0.05$ according to Tukey's Honestly Significant Difference test. Reported means followed by lowercase letters differ among the whole soil, soil fraction within specified depth. Error bars represent standard errors of the mean.

sampling distances in the 250–2000 μm fraction below 50 cm may be attributed to rhizodeposition by cork oak roots.

The smaller 53–250 and $<53 \mu\text{m}$ soil fraction sizes demonstrated no differences in C storage at any sampling depth (Fig. 1). Improved soil edaphic conditions closer to the tree may have promoted the inclusion of silt + clay aggregates in larger micro- and macroaggregates, and as such differences may not be evident from the separation techniques used in this study. Six *et al.*⁴⁵ demonstrated preferential silt + clay protection within microaggregates and macroaggregates on no-till grassland site as compared to a tilled site. Protection of stable silt + clay aggregates within larger size aggregates is likely. It may be that silt + clay sized aggregates are held within micro- and macroaggregates closer to the tree, but this conjecture could only be validated by

destruction and analysis of macroaggregates and microaggregates that are theorized to contain silt + clay aggregates. The deep-rooted nature of cork oak, an adaptation for surviving lengthy summer droughts, provides a deeper horizon source of C to the soil than herbaceous species, and promotes the preferential storage of C in the 250–2000 μm soil fraction. Thus, storage of C in the macroaggregate size class increased under the tree canopy as compared to the open native pasture.

Carbon storage in whole soil

While cork oak roots may proliferate in the 0–100 cm range and below, roots from herbaceous species, inputs of organic matter from tree leaf fall and animal excreta are also likely additional

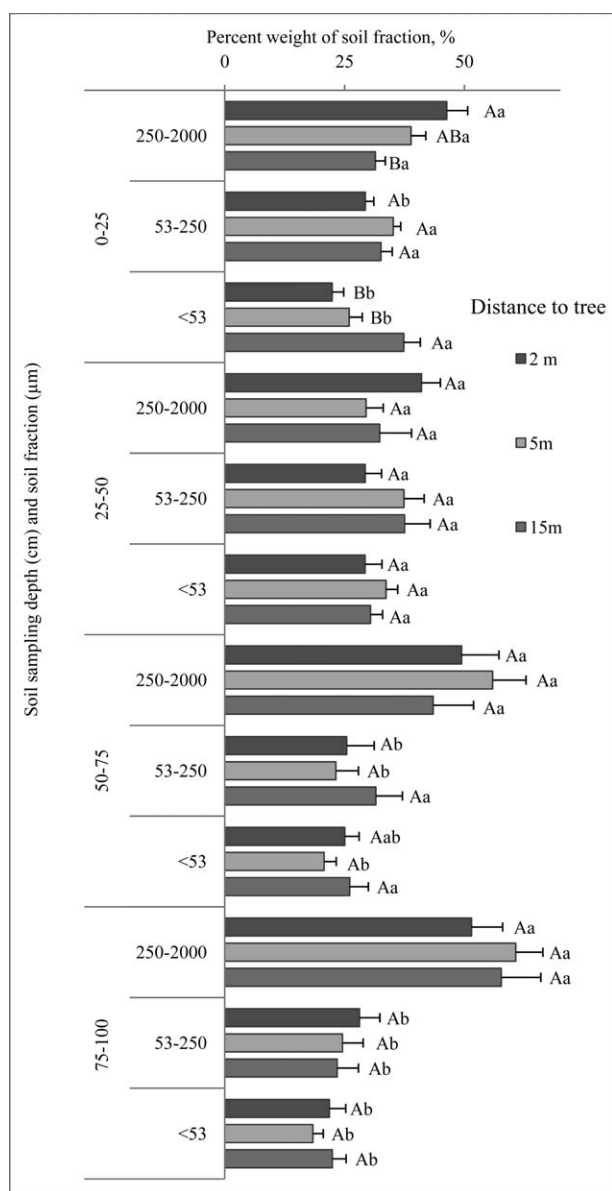


Fig. 2 Mean percentage recovery from fractionation procedure by weight in three soil fractions (250–2000 μm , 53–250 μm , and <53 μm) at four soil depths (0–25, 25–50, 50–75, and 75–100 cm) at three distances (2, 5, and 15 m) from individual cork oak trees (*Quercus suber*) at the St Esteban farm, Extremadura, Spain. *Means followed by different uppercase letters differ among distances to tree within the whole soil, soil fraction and sampling depth at $p < 0.05$, according to Tukey's Honestly Significant Difference test. Reported means followed by lowercase letters differ among the soil fraction at specified depth. Error bars represent standard error of the mean.

sources of C input to the upper soil horizons.³² In the shallowest sampling depth (0–25 cm) a doubling of mean soil C was seen from 15 to 2 m to the tree (Fig. 2). The numbers of roots in herbaceous species in the Mediterranean as well as elsewhere, on the other hand, are highest closer to the soil surface and decrease significantly with depth. Silva and Rego⁴⁶ described the root counts for several herbaceous and shrubby species in southern Portugal, demonstrating a niche separation of resource use between species such as deep-rooted shrubs that can draw on soil

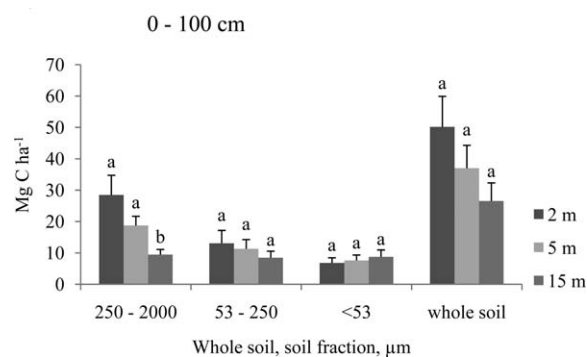


Fig. 3 Mean carbon storage (Mg C ha^{-1}) in the whole soil and three soil fractions (2000–250 μm , 250–53 μm , <53 μm) to 1 m soil depth at three distances (2, 5, and 15 m) from individual cork oak trees (*Quercus suber*) in Dehesa silvopasture, Extremadura, Spain. *Mean C storage within the whole soil, soil fraction labeled with different lowercase letters differs by $p < 0.05$, according to Tukey's Honestly Significant Difference test. Error bars represent standard errors of the mean.

moisture deeper in the soil in summer and more shallow-rooted species that take advantage of seasonal rainfall in winter. Herbaceous species are also likely to produce more fine roots as compared to shrubs. In the St Esteban Dehesa, cork oak roots more deeply than herbaceous species, and micro-site improvements closer to the tree⁴⁷ improve growing conditions for herbaceous species in the upper soil profiles when water is available. Cork oaks probably also take advantage of these seasonal improvements. During fieldwork at the St Esteban farm in January 2008, growth of the native pasture grasses was noticeably enhanced under the oak trees (Fig. 4). As cork trees are a source of C seasonal species, as well as cork oak, take advantage of the higher nutrient status and other soil fertility improvements under the tree during the winter and spring months.^{47–49} Lopez *et al.*⁴⁸ found higher annual fine root biomass for *Quercus ilex* in winter months in northeastern Spain when soil water was available. While the presence of animals in the typical Dehesa system may help to increase soil nutrients around trees (from excreta) and add to greenhouse gas emissions from methane,⁷ these effects are not the focus of this study. These results are important in the context of the emerging body of research that demonstrates greater retention of root-derived C, compared with residue (shoot)-derived C, in SOM,⁵⁰ suggesting greater contribution of root C than residue C to overall C stabilization in soil.

Total carbon stock in the farm

While significantly more soil C was found underneath the tree canopy, only 27.5% of the land at the St Esteban farm is underneath the tree canopy (assuming a uniform 5 m drip line with 35 stems ha^{-1}). Taking into account the remaining land cover (72.5% native pasture), 29.9 Mg C ha^{-1} was estimated for mean soil C at St Esteban for a total of 3.6 Gg C for the whole farm. Moreno *et al.*⁴⁷ showed that the positive influence of individual *Quercus ilex* trees on soil chemical properties only extends barely past the drip line, representing about 15% of the land on a less dense, 20 stems ha^{-1} Dehesa located in the same region of Spain. Higher density Dehesas, as is the case for the



Fig. 4 Photograph demonstrating enhanced winter understory growth underneath Holm oak tree (*Quercus ilex*), taken on January 18, 2008 at the St Esteban farm, Extremadura, Spain.

St Esteban farm and, all other factors equal, will lead to greater tree influence on the landscape, a 13% increase in tree cover per hectare when tree density increases from 20 to 35 stems ha^{-1} . As such, increasing densities of trees in the Dehesa where possible, especially where trees have been lost to disease or removal, can be expected to lead to greater landscape-level soil C storage.

The estimated C storage on a hectare basis is on the low end of Spanish soils but well within the standard deviations of several reported land uses that coincide with the Dehesa agrosilvopastoral system.¹² Whole field storage of C is similar to typical regional land uses such as olive groves (*Olea europaea* L.), pastures, a pasture-broadleaf mix, and dry land farming,¹² each of which may serve as proxy for the Dehesa system under study. Turrión *et al.*⁵⁰ found 33 Mg C ha^{-1} in a nearby Spanish *Quercus pyrenaica* forest at a similar altitude and climate. Comparing the whole field C result with other sites reveals interesting similarities in storage in agroforestry systems in some very disparate sites. Nair *et al.*² reported results for total soil C (given particular sampling depths) for several agroforestry systems worldwide, including 27.4 Mg C ha^{-1} for *Gmelina arborea* and crop mix in central India, 33.3 Mg C ha^{-1} for a *Faidherbia albida* parkland, in Nigeria, and between 6.9 and 24.2 Mg C ha^{-1} for a *Pinus elliottii* and *Paspalum notatum* mix in Florida, USA. The C storage value (20–40 Mg C ha^{-1}) estimated for the Mediterranean Spain in this study is within the range of potential C storage values for parklands and grazing lands in the arid and semiarid lands as reported by Nair *et al.*²

Carbon stock in soil aggregates as a component of environmental monitoring

The differences in C stock at different microsites (lateral distances from trees and soil depths) in this study site are indicative of a general problem in C accounting procedures. Even within such a seemingly “homogeneous” farm, the C content ranged considerably between and among sampling locations. Such differences will be of much higher magnitude when different soil orders, land-use systems, and ecological conditions are considered. In a multi-location study of several

AF systems summarized by Nair *et al.*,⁷ total SOC ranged from $<1 \text{ g kg}^{-1}$ in Alfisols of Mali, West Africa, to 45 g kg^{-1} in Oxisols of Bahia, Brazil (these data are presented here in g kg^{-1} rather than Mg ha^{-1} considering the substantial differences in bulk density of the soils). Yet, most policy documents and projections are based on a single, uniform value, or a narrow range of values, for C stock and C sequestration potential (CSP) of LUS irrespective of their site conditions and system characteristics. For example, the IPCC estimate of a global value of 630 million ha of unproductive croplands and grasslands that could be converted to agroforestry, which could potentially sequester 1.43 and 2.15 Tg of $\text{CO}_2 \text{ y}^{-1}$ by 2010 and 2040, respectively,⁵² is based on such “representative” values. It is important that inherent variability among soils to store C is factored into such global projections, especially in the context of high priority given to efforts on quantification of ecosystem benefits and services of agricultural systems.

Carbon sequestration being the process of transfer of C, especially CO_2 , from the atmosphere and its secure storage in long-lived pools,⁵² sequestered C in soils can be taken as the ‘stable’ C that is present in finer ($<250 \mu\text{m}$) fractions of soils. However, considering the protection of microaggregates and SOM by macroaggregates as discussed above, a considerable amount of SOC within the macroaggregate fraction can be relatively stable. Total C determinations give values of all C in soil (including C held in finer fractions, macroaggregates, and particulate OM), all of which do not represent sequestered C. Thus, total C *per se* may have only limited value in C sequestration calculations. The results from this study could be integrated with other already available data to develop an index (or a range of indices) depending on soil type, land-use history, *etc.*, which could be applied to the total SOC value to obtain the C sequestration potential of that soil. A quantitative measure could thus be available showing the relationship between total C content, land-use systems, and aggregate type to give better estimations of the extent of C sequestration in land-use systems.

Conclusion

Data from the study of Spanish Dehesa silvopasture indicate that silvopasture with cork oak trees store more C in soils as compared to soils under native pasture alone. Soil fractionation revealed significantly greater C storage in the 250–2000 μm (macroaggregate) size class at distances closer to individual trees. In conjunction with other factors such as ecology and land-use practices, the C content in soil aggregate classes, rather than the total C content *per se*, could be used to develop better indicators of C sequestration potential of the soil and thus for field-scale environmental monitoring. The enormous variations among soils in their C stock and C sequestration potential will need to be factored in while projecting estimates of C sequestration potential of land use systems. The general neglect and decline of the centuries-old Dehesa system on the Iberian Peninsula over the past few decades, by a combination of biological and management factors, may have the secondary effect of reducing C inputs to long-term soil storage processes.

Acknowledgements

This study would have not been possible without the financial support of the Center for Subtropical Agroforestry at the University of Florida, the Alumni Association of the University of Florida, the Institute of International Education's Fulbright Scholar Program, the Spanish Ministerio de Ciencia y Tecnología (MODE project; AGL2006-09435/FOR). Victor Rolo Romero provided invaluable assistance in the field.

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