

# Carbon Sequestration in European Agroforestry Systems

M.R. Mosquera-Losada, Dirk Freese, and A. Rigueiro-Rodríguez

**Abstract** Agroforestry systems (AFS) are recommended for Europe through the European Rural Development Council regulation 1698/2005, in recognition of their role in reducing carbon (C) emissions and promoting C sequestration which would help to fulfil the Kyoto Protocol requirements. These systems have been found to be a good tool to reduce fire risk and C release in southern European countries. The implementation of AFS could also reduce C release to atmosphere because of the value given to non-timber products, thereby reducing chances for clear cutting of trees. Furthermore, the tree component in AFS will add C into the soil through litterfall and root decomposition, which takes place at deeper soil layers than under agronomic crops or pasture. Tree management practices such as regulating tree density and planting arrangement will influence the C sequestered in the system. Compared with the tree components, the understory components of AFS have less impact on the total C sequestration. The higher inputs of residues generated by the trees in AFS than in tree-less systems may cause high soil C sequestration potential, but soil C increase depends on the incorporation and mineralization of C in the soil, which are affected by understory crop management practices.

**Keywords** Alley cropping • Fire protection • Kyoto protocol • Silvopasture • Soil organic matter (SOM)

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## Introduction

During the last century, the climate in Europe has changed more than in other areas of the world (IPCC 2007). Compared to the pre-industrial era, when the mean annual temperature increased by 0.8°C globally, it increased by 1.2°C in Europe. Based on theoretical models, a further increase of 1.0–5.5°C is expected by the end of the twenty-first century (Christensen et al. 2007). The increase in temperature has been most apparent in hilly areas such as the Alps, which tend to have high biodiversity and where temperature increased by 2°C during the twentieth century (EEA 2009a). This is twice the average temperature increase for the northern hemisphere. In addition, the quantity and distribution of precipitation have also changed in Europe during the twentieth century. Although there has been a 20% decrease in rainfall in southern Europe, there has been a 10–40% increase in rainfall in northern Europe. Furthermore, an increase in the frequency of extreme weather events is predicted across the European continent (EEA 2008).

Climate change may lead to an increase in the incidence of wildfire outbreaks, a decrease in biodiversity, and an increase in carbon dioxide (CO<sub>2</sub>) emissions. Wildfires are a serious threat to forest ecosystems in Europe (Rigueiro-Rodríguez et al. 2009a), and represent a major source of CO<sub>2</sub> emissions. Any increase in temperature will aggravate the danger of forest fires by increasing the incidence of fire events, the area burnt, and the duration of fire seasons, especially in southern and central Europe (EEA 2008). Moreover, climate change in Europe may modify biodiversity through habitat loss and cause changes in dispersal capacity, phenological characteristics, life cycles, and food sources of native species. Climate change may also provoke the decoupling of predator-prey relationships, new invasions, or the spread of already established invasive alien species (EEA 2009b). It would also lead to a decline in soil organic carbon (C) stocks and an increase in CO<sub>2</sub> emission from soils. Soils may become more susceptible to erosion, especially in the Mediterranean areas where annual soil losses may reach 200 Mg ha<sup>-1</sup> (Correal et al. 2009). Soil degradation is already intense in parts of the Mediterranean and central Eastern Europe and may contribute to desertification (EEA 2008). Agroforestry systems (AFS) offer solutions to some of these climate change related ecosystem management problems. For example, AFS have proved to be an excellent fire prevention technique in many parts of southern Europe such as France (Etienne 1996; Etienne et al. 1996; Rigolot and Etienne 1996), Greece (Papanastasis et al. 2009), and Spain (Robles et al. 2009; Rigueiro-Rodríguez et al. 2009b). Agroforestry practices are considered good land management tools to enhance biodiversity (Rois-Díaz et al. 2006; Rigueiro-Rodríguez et al. 2011b) and augment C sequestration, compared with tree-less systems worldwide (Nair et al. 2008, 2009).

The Kyoto Protocol establishes that land use, land use change and forestry (LULUCF) activities such as afforestation, reforestation, and deforestation (Article 3.3), and forest land management, cropland management, grazing land management, and revegetation (Article 3.4) can be used to meet the greenhouse gas (GHG) emission reduction goal (UN 1998). Burley et al. (2007) indicated that forest offset projects can be based on two approaches, namely, (a) the absorption of GHG by new vegetation

(i.e., sink creation and sink enhancement), and (b) displaced emissions by existing vegetation (i.e., fire risk reduction and avoided deforestation). Emission from timber harvesting, which also negatively affects soil organic matter (SOM), could be reduced by the adoption of agroforestry systems that provide benefits other than timber from forest areas. Austria, Belgium, Denmark, Finland, Ireland, Italy, Luxembourg, the Netherlands, Portugal, and Spain plan to fulfil their assigned C emissions by using the Kyoto mechanisms described in Articles 3.3 and 3.4. However, Spain and Italy are among the EU countries with the greatest focus on increasing atmospheric CO<sub>2</sub> removals by enhancing C sink activities. Therefore, the implementation of AFS in these two countries, aimed at reducing CO<sub>2</sub> in the atmosphere through the two LULUCF activities described by the Kyoto Protocol, should be greater than in other European countries (EEA 2009c).

Considerable efforts in land use change for the reduction of GHG emissions have been carried out in Europe. More than one million hectares of forests were planted between 1994 and 1999 in Europe (Rois-Díaz et al. 2006). According to current targets, it is expected that more than 650,000 ha of agricultural land and about 240,000 ha of non-agricultural land will be afforested in Europe during the period 2007–2013 (EU 2009). This process will involve more than 12,000 landowners. The most recent European Rural Development Report estimates that AFS will cover 60,000 ha of agricultural lands representing 3,000 landowners during the period 2007–2013 (EU 2009) as a result of the council regulation 1698/2005 (EU 2005).

## Agroforestry and Carbon Sequestration

The C sequestration potential of AFS is based on live components growing up within the system including the soil, but should also include activities such as forest fire prevention and other multifunctional outputs from the system (Rigueiro-Rodríguez et al. 2009b). The potential of C sequestration in AFS is dependent on the tree component (Nair et al. 2009). Tree presence would increase C sequestration per unit of land due to the C sequestered by the tree itself, the inputs of residues (leaves and branches) it makes on the soil, and the incorporation of roots into the soil. Trees use a greater volume of soil to build up SOM than herbaceous crops, as they are able to explore soils farther from the tree trunk and to a greater depth, assuming small tree density is used (Moreno et al. 2005). The greater soil volume explored by tree roots would enhance belowground organic matter depositions (Howlett et al. 2011). However, understory species may also be positively or negatively affected by the tree presence. The symbiotic or competitive relationship of these components (i.e., tree and understory) depends on specific edapho-climatic conditions (Rigueiro-Rodríguez et al. 2009a; Mosquera-Losada et al. 2010a). Conditions such as adequate water regime, optimal temperatures, and soil nutrient availability would promote tree growth (López-Díaz et al. 2010), but in areas with strong water deficits, usually development of pasture (or other understory species used in the AFS) is reduced due to the presence of trees.

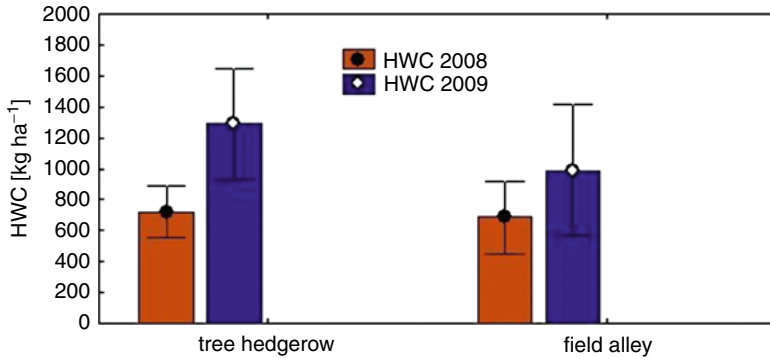
Agroforestry as a land use option has great potential for C sequestration in Europe, as it allows for the sequestration of more C per unit of land, compared with tree-less agronomic systems (Matos et al. 2010a). Agroforestry also results in higher annual economic returns per unit of land through the whole life cycle than in exclusive forestry systems where the revenue is generally only realised at final harvest. These returns could be further increased if appropriate land management practices mainly regulating tree density and distribution are adopted (Sibbald 1996; Fernández-Núñez et al. 2007). The role of AFS in the reduction of C emissions derives from the prevention of forest fires in Mediterranean Europe, as silvopasture agroforestry practices reduce the understory woody biomass (Etienne et al. 1996; Rigueiro-Rodríguez et al. 2009b, 2010). Most AFS have also been shown to reduce soil erosion, and improve nutrient cycling, water availability for crops, soil faunal activities, and soil fertility, while at the same time sustaining high levels of crop production (Grünewald et al. 2007; Quinkenstein et al. 2009; Rigueiro-Rodríguez et al. 2009a).

Some of the most important options to increase C sequestration are those dealing with LULUCF measures. Currently, most European forests are relatively young and they act as a C sink. Growing forests sequester C, but when they reach maturity, the C annually sequestered is reduced. For this reason, forested land conservation that avoids total clear felling should be better at reducing C emissions in the future, not only because of C exported in the harvested trees, but also due to C soil emissions, once the trees are harvested (Nair et al. 2009). However, Dresner et al. (2007) highlighted that if cut timber is worth more than trees still standing in the forest, there is no incentive for farmers to protect the forest. As such, deforestation is likely to occur, regardless of the wider impacts of this such as C emissions. Nonetheless, if the agronomic component of an AFS is valuable for farmers, this would be an additional reason to prevent deforestation and thus reduce CO<sub>2</sub> emissions (Dresner et al. 2007).

Several types of agroforestry practices are currently implemented in Europe. Silvoarable and silvopasture agroforestry practices are the most prevalent in Europe in terms of the area under those practices compared with other agroforestry practices (Eichhorn et al. 2006; Mosquera-Losada et al. 2009). They are mostly carried out in Spain and Portugal, but also in Germany, France, Italy and the UK (Dupraz et al. 2005; Grünewald et al. 2007; Mosquera-Losada et al. 2010a; Quinkenstein et al. 2009).

The tree component of an AFS may be more efficient at CO<sub>2</sub> utilisation from the atmosphere and may have higher C returns to the soil through their litter than herbaceous crops (Gordon et al. 2006). One year after the implementation of an agroforestry system (Böhm et al. (2010), the content of organic C in soil under tree hedgerows was significantly higher as compared to field alleys (Fig. 1) in Germany, due to the higher root development in the hedgerows compared with the field alleys.

In agroforestry systems, C is located in five main pools, namely, aboveground plant biomass (tree and understory), plant roots (tree and understory), litter, microbial, and soil C. These pools interact with each other via different pathways of transformation and translocation, e.g., plants absorbing CO<sub>2</sub> from the atmosphere during



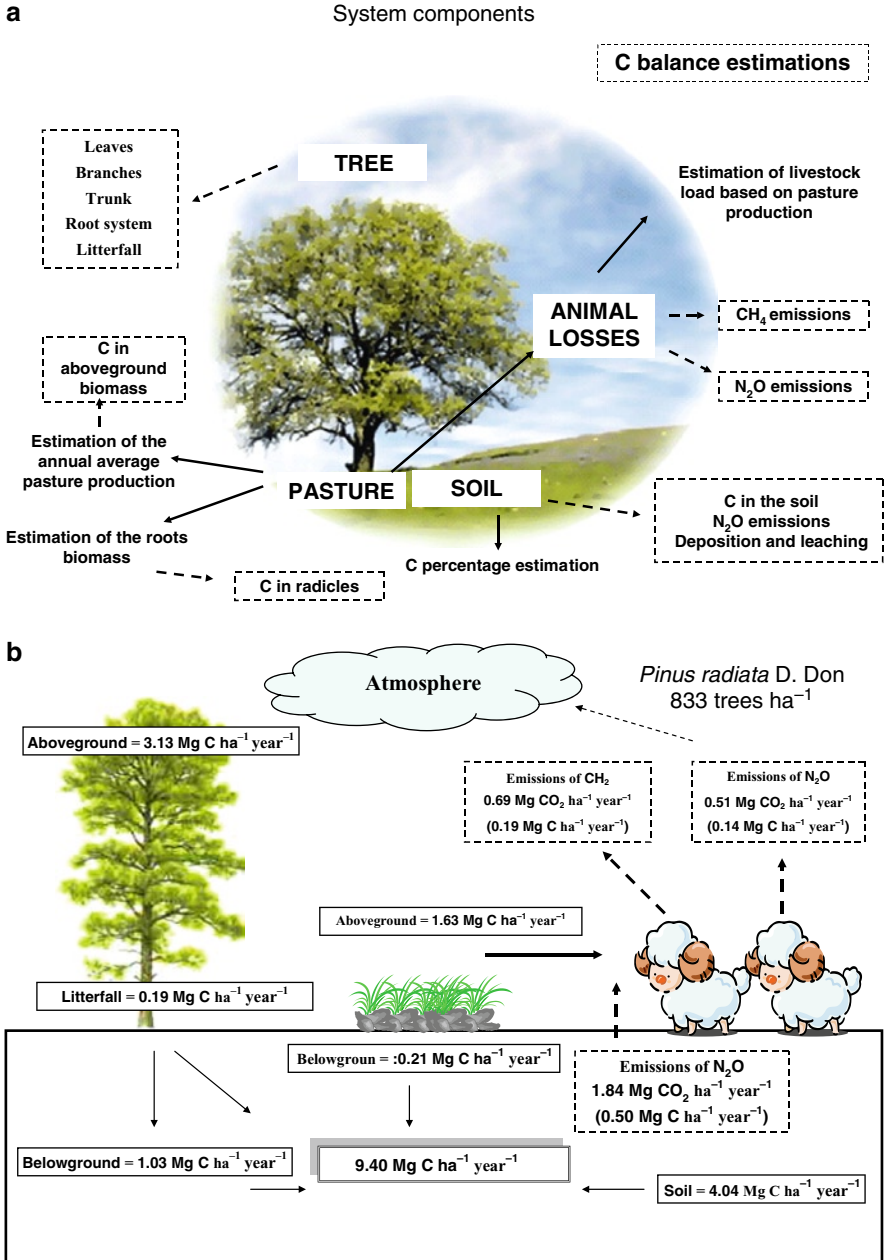
**Fig. 1** Hot water extractable organic carbon in the surface (0–30 cm) soil, 1 year (HWC 2008) and 2 years (HWC 2009) after establishing an alley cropping system, in a mining reclamation landscape, Lower Lusatia, north-eastern Germany (Source: Adapted from Böhm et al. 2010)

photosynthesis. Some  $\text{CO}_2$  is released back to the atmosphere in the process of plant respiration. Litter falling from plants and dead roots from plant material are decomposed into soil C. Some of the soil C is taken up by microbes and stored, and some becomes mineralised. Soil stores C, but as a result of the mineralisation and root respiration, part of that C is released back to the atmosphere. Furthermore, biodiversity enhancement by AFS facilitate a better nutrient use and therefore increases C sequestration compared with tree-less agronomic systems (Howlett et al. 2011; Rigueiro-Rodríguez et al. 2011b).

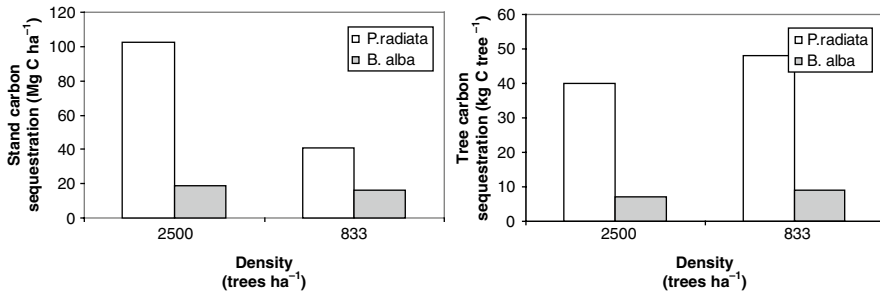
Measurement of C sequestration following land use changes from tree-less agriculture to forestland requires the evaluation of the baseline C stocks as well as the nature of the tree component and the modifications the tree causes to the understory and in the soil compartment. If silvopasture agroforestry is carried out, then the animal component and the emission of methane and nitrous oxide gases should also be taken into account (IPCC 2007). The main components and their GHG balance in a silvopasture agroforestry system including grazing animals are presented in Fig. 2.

### *Tree Component*

Land use change through afforestation or reforestation should increase C sequestration per unit of land and the rate of C sequestered by trees within a system will depend on tree species, age, and density (Quinkenstein et al. 2009), besides the edapho-climatic conditions, management, fertilization, and land clearing, among others. Carbon sequestration by an individual tree can be estimated by allometric equations based on the tree diameter that have been recently developed in Spain (Montero et al. 2005) and Europe (Zianis et al. 2005). In their studies, 13 and 24 conifers and 15 and 31 broadleaf trees species were used to estimate the C sequestered in



**Fig. 2** Carbon pools in a silvopasture system including GHG emissions: (a) A schematic diagram showing the different compartments. (b) An example of the estimated quantities in each compartments in a 11 years-old *Pinus radiata* D. Don stand in Galicia, NW Spain (Source: Adapted from Fernández-Núñez et al. 2010)



**Fig. 3** Carbon stock in the tree stand and individual tree of *Pinus radiata* D. Don and *Betula alba* L. Eleven years after establishment at two densities (833 and 2,500 trees/ha<sup>-1</sup>) in Galicia, NW Spain

aboveground biomass and in roots, respectively. This was carried out for species from the Mediterranean, mountainous, and Atlantic biogeographic regions of Europe. However, most of the trees used to develop the equations were in mature, dense stands, and therefore, more research is needed to understand how C is sequestered in younger stands (Knopka et al. 2010) and growing at lower densities such as in AFS.

The growth rate of tree species is a significant factor in promoting C sequestration. Annual estimates of C sequestered by tree biomass of *Eucalyptus globulus* Labill, *Pinus pinaster* Ait., *Pinus radiata* D. Don and *Castanea sativa* Mill. in Spain were 5.14, 1.58, 1.11, and 0.52 Mg C ha<sup>-1</sup>, respectively (Pardos 2010). Differences in growth rates explain why, after 10 years, *P. radiata*, a species with a high growth rate, sequestered eight times more C per tree than *Betula alba* L. at densities of 833 and 2,500 trees ha<sup>-1</sup> in Spain (Fig. 3). Similarly, species like poplar or eucalyptus were able to sequester C faster than species such as *P. radiata*, *B. alba*, *P. pinaster*. However, these three species grew and sequestered C faster than the other common silvopastoral tree species such as *Pinus sylvestris* L., *Quercus petraea* L., *Quercus robur* L., or *Fagus sylvatica* L. (Pardos 2010). Gordon et al. (2006) highlighted the importance of using fast growing tree species in silvopastoral systems to reduce C emissions in Canada. They estimated that net C sequestration of a poplar-based silvopastoral system was almost three times more than that reached by a monoculture pasture system. However, if trees grow quickly, C sequestered for a given period of time is reduced as trees will be harvested earlier (Fernández-Núñez et al. 2010). The time required for C sequestration to occur is longer for slow growing species than for fast growing species. Therefore, once harvested, the fast growing species emit C into the atmosphere earlier than slow growing species, mainly from SOM mineralization. Moreover, sawn timber production is usually associated with slow growing species, which are retained for longer time than pulp and paper from fast growing species such as *Eucalyptus* spp.

The production of *Robinia pseudoacacia* L. in an alley cropping system has received considerable interest in Germany as an alternative to agricultural crops as well as an additional wood source, while simultaneously acting as a potential C sink to counterbalance greenhouse gases emissions. Average aboveground

biomass production of *R. pseudoacacia* ranged from 0.04 to 9.5 Mg ha<sup>-1</sup> year<sup>-1</sup> for 1–14 years of growth, respectively on reclaimed sites in north-eastern Germany (Quinkenstein et al. 2011).

The C sequestration of afforested or reforested lands also depends on land management and soil type. Fertilization carried out to enhance crop production in AFS indirectly increases tree growth in some edapho-climatic conditions (Dupraz et al. 2005). In acidic soils of Galicia, Spain (water pH=4.5), the C sequestered by *P. radiata* (1,667 trees ha<sup>-1</sup>) 11 years after afforestation was 4.09 Mg C ha<sup>-1</sup> when no fertilizer was applied. The amount of C sequestered by the tree component significantly increased to 7 Mg C ha<sup>-1</sup> when sewage sludge was used as fertilizer in the same soil. However, these values were lower than those reported for agricultural lands (initial soil water pH=6.9), which were afforested at high density (2,500 trees ha<sup>-1</sup>) (Fig. 3; Fernández-Núñez et al. 2010). Soil fertility improvements usually increase growth rates and symbiosis. However, facilitation between the tree and the understory should be promoted in the early tree ages in order to enhance resource use and increase C sequestration (Mosquera-Losada et al. 2006, 2011b). The use of legumes such as clover (*Trifolium* spp.) in the sown mixture, increased tree growth and was found to promote symbiosis between *P. radiata* and understory (López-Díaz et al. 2010). However, the increase in ryegrass (*Lolium perenne* L.) density during the year of plantation establishment reduced *P. radiata* growth due to competition between the tree and ryegrass for soil resources (Mosquera-Losada et al. 2011b).

Tree density is another factor that affects C sequestration. Fernández-Núñez et al. (2010) reported from Galicia, Spain, that land that had previously been under agriculture when afforested with *P. radiata* at 833 or 2,500 trees ha<sup>-1</sup> was able to sequester 40.8 and 102.4 Mg C ha<sup>-1</sup> 11 years after plantation in tree roots and above-ground biomass, respectively, despite the fact that C sequestered per tree was higher at a low density (48 and 40 kg C tree<sup>-1</sup>, respectively: Fig. 3). Similar results were also found for *B. alba* planted at these densities in the same area.

In the Atlantic biogeographic region of Europe, tree stands were established at higher tree densities than in the Mediterranean dehesa area to promote timber production (Serrada et al. 2008). Due to the intraspecific competition in the high density stands, tree roots may not spread far away from the tree trunks compared with low density stands. There have been few published studies where the differences in root system profiles with respect to the distance from the tree for low versus high density stands have been measured. In the Mediterranean environments, Moreno et al. (2005) reported that most fine roots of *Quercus ilex* L. trees were below 80 cm depth, while herbaceous plant roots were mainly located in the top 30 cm soil layer. Drought conditions could have a great effect on tree root distribution within the soil profiles of Mediterranean systems. The same effect could be simulated by competition within the herbaceous layer in more northern European countries if AFS with low tree densities were implemented. If tree roots are located below the herbaceous understory rhizosphere, then competition for soil resources between trees and herbaceous plants is reduced. Implementation of agroforestry could increase the volume of soil explored by roots (the upper part of the soil explored by the herbaceous



component and the lower part by the tree component) in low density stands compared with tree-less pastures. The amount of fine roots that are considered to be the main source of organic matter within a soil C pool (Dresner et al. 2007) would also increase.

Tree C sequestration also depends on the species. Evergreen trees retain C in the leaves for longer period of time than deciduous tree species, which cause regular inputs of organic matter into the soil, apart from the roots. Evergreen tree litterfall is usually low until canopy closure. Afterwards, the relatively low understory light levels may cause an accumulation of litter on the forest floor. Density affects the dynamics of the tree litter inputs into the soil. A dense *P. radiata* canopy caused an accumulation of a thick litter layer of several centimetres above the soil a few years after canopy closure, which prevented herbaceous plant establishment and reduced biodiversity and soil C sequestration potential. Litter biomass also depends on tree density, which was higher in high density forests (6.25 Mg ha<sup>-1</sup> at 2,500 trees ha<sup>-1</sup>) than in low density stands (4.26 Mg ha<sup>-1</sup> at 833 trees ha<sup>-1</sup>) in a *P. radiata*-afforested land 11 years after planting (Fernández-Núñez et al. 2010). The thick litter layer could emit large quantities of C once the forest stand is harvested. However, no accumulation of litterfall on the soil was observed in a silvopastoral system established with *B. alba* at 2,500 trees ha<sup>-1</sup> or 833 trees ha<sup>-1</sup> due to the low growth rate of birch as compared with radiata pine. Higher soil temperatures in birch stand, comparable with *P. radiata*, increased birch litter decomposition, promoting soil C sequestration (Howlett et al. 2011).

### ***Understory Component***

Compared to the tree and the soil C pools, the amount of C sequestered in the understory component of the AFS is relatively small (Fernández-Núñez et al. 2010). In European AFS, the understory component may be a crop (e.g., a cereal or leguminous crop) in the silvoarable systems or herbaceous or woody plants in the silvopastoral systems. Arable systems have lower C sequestration potential than herbaceous pasture or understory woody plants and involve annual crops that are usually harvested within a year of sowing, and the biomass is exported from the system. Crop management practices such as plowing, liming, and fertilization may cause either soil C increase or losses. Improvement of soil fertility increases the growth of AFS components and therefore soil inputs of C. However, management activities may also result in better aeration, increased pH, and enhanced soil fertility, promoting microbial activity and organic matter mineralisation, in turn, leading to lower SOM levels (Reijneveld et al. 2010).

Perennial grasslands and shrublands may store C within their tissues for a longer period of time than arable crops. The large area of the European Union allocated to grasslands in different biogeographic regions (33% and 25% of the Atlantic and continental biogeographic regions of Europe; EEA 2006) offers a high potential for C sequestration. This potential, however, is dependent on the edapho-climatic

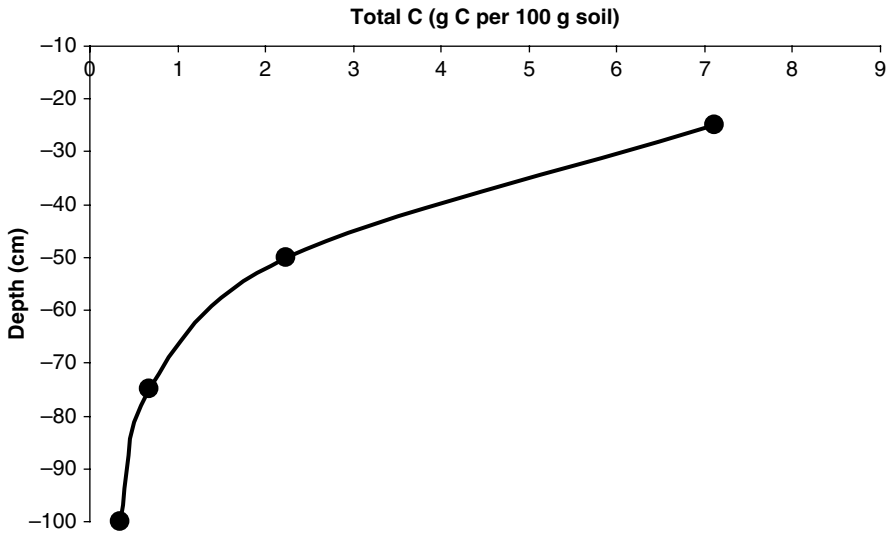
conditions and land management practices adopted (Follet et al. 2001; Schanabel et al. 2001). The input of organic matter to grassland soils is very important (Sanderson and Wätzold 2010) and would increase the SOM content. Mature pasturelands, however, show no net annual C uptake when all sources and sinks are considered (Suyker and Verma 2001; Gianelle et al. 2004). Follet et al. (2001) concluded that improved grassland management could enable C sequestration to continue for 25–50 years until a new equilibrium of soil C content is reached. After that, the improved grasslands would no longer serve as C sinks. Even though grasslands may sequester C, grazing by livestock animals may result in CH<sub>4</sub> or N<sub>2</sub>O emissions (IPCC 2007). When the animal stocking rate is adjusted to the production of grasslands, the C losses with GHGs are offset by the C sequestered (Fernández-Núñez et al. 2010).

Understory shrubs sequester more C than herbaceous plants. However, the risk of C emissions caused by fires associated with forestlands is increased by these shrubs, making the presence of woody vegetation understory very hazardous in the Mediterranean countries of Europe and in the southern Atlantic biogeographic region of Europe, where summers are too dry and fire risk is high (Rigueiro-Rodríguez et al. 2009b). Prevention of forest fires mitigates C emissions (Burley et al. 2007). Agroforestry practices could be successfully implemented to reduce the emissions of C caused by fires. For instance, shrub grazing by goats in silvopastoral systems reduces the amount of combustible vegetation in the understory and encourages a less flammable herbaceous layer (Rigueiro-Rodríguez et al. 2011a). Understory vegetation transformation from shrubs to a grass is thus promoted by grazing of shrubs by animals as well as by soil nutrient cycling through animal faeces and urine deposition (Rigueiro-Rodríguez et al. 2009b).

## ***Soil Component***

The soil represents the most important pool of C storage in terrestrial ecosystems, accounting for about 75% of total stored C (Lal 2005; Dresner et al. 2007). Soil C sequestration depends on edapho-climatic conditions, which may increase or reduce the organic matter inputs (i.e., the quantity of plant residues), incorporation of organic matter into the soil, and organic matter mineralisation (Nieder et al. 2003). Soil properties such as clay content determine the extent of C enrichment in humus. Organic matter inputs usually create a C gradient from the surface to the lower layers of the soil worldwide (Fig. 4; Howlett et al. 2011).

Temperature and humidity are the main drivers of SOM production, incorporation, and mineralisation (Theng et al. 1989). If temperature and humidity are optimal for aboveground biomass production as in the Atlantic climate, the inputs of organic matter into the soil are greater than that in less favourable climatic conditions such as in the Mediterranean climate. For this reason, the higher potential productivity of crops in the Spanish Atlantic region is an important indicator of higher SOM as compared to the Spanish Mediterranean region (i.e., 3 and 0.4 Mg ha<sup>-1</sup> year<sup>-1</sup> for



**Fig. 4** Total soil carbon concentration by depth in an afforested and non-fertilized soil in Galicia, NW Spain

Atlantic and Mediterranean regions, respectively: Pardos 2010). In the dehesas located in the Mediterranean area, the presence of mature trees and, therefore, the rate of incorporation of their residues are associated with higher SOM levels below the tree than away from the tree in AFS established under trees without canopy closure (Moreno and Obrador 2007). In some cases, the degree of incorporation of plant residues into the soil may be restricted by high humidity and low temperature. In *P. radiata* stands, the closure of tree canopies caused an annual accumulation of about 7 Mg ha<sup>-1</sup> of litterfall in Galicia (Fernández-Núñez et al. 2010).

Roots are also an important part of the C balance in terrestrial ecosystems because they transfer large amounts of C into the soil. More than half of the C assimilated by the plant is transported belowground via root growth and turnover, root exudates (of organic substances) and litter deposition, and roots may contribute up to 33% to C sequestered in ecosystems (Fernández-Núñez et al. 2010). The dynamics of growth, decay, and root turnover are some of the least understood aspects of belowground interactions in agroforestry (Nair et al. 1999). There is much information on C sequestration in the topsoil layer of 0–20 cm. However, information on deeper soil layers, where most of the tree roots occur, is lacking in most environments, but some studies have been carried out in the Spanish dehesa agrosilvopastoral system (Moreno and Obrador 2007). Roots of trees and grass or crops have different root length and depth profiles. Tree roots are longer and deeper in soil than grass or crop roots, and in soils under trees, a considerable amount of C is stored below the plow layer (50 cm). This C is also better protected from disturbance, which leads to longer residence time in the soil. Most of the root biomass of annual crops and grasses

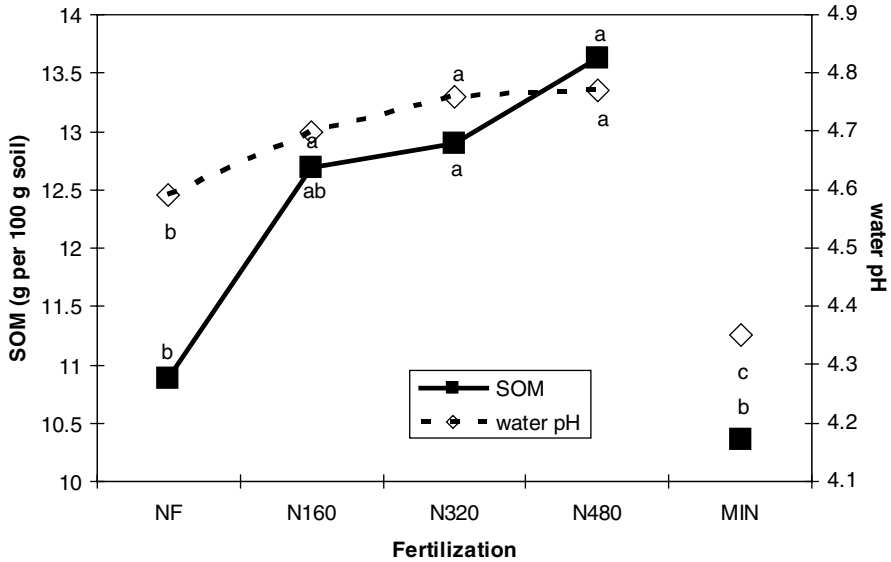
consists of fine roots (diameter < 2 mm). Fine roots of both trees and crops have a relatively fast turnover (measured in days to weeks), but lignified coarse roots of trees decompose much more slowly once trees are harvested and may contribute substantially to belowground C pools (Vanlauwe et al. 1996).

Carbon inputs to the soil are also affected by litterfall. Higher biomass production per tree and per hectare obtained in previously agricultural lands afforested with *P. radiata* and *B. alba* at high stem density increased soil C more than low tree density 5 years after the establishment of both trees (Fernández-Núñez et al. 2010). However, differences in SOM between density treatments or species disappeared 10 years after afforestation, probably due to the lack of litterfall incorporation under high density stands. This can be explained by the low temperatures and high humidity experiences differentially by both systems. Incorporation of residues into the soil is the first step to increasing SOM.

Alley cropping systems have also come into focus in the reclamation of post-mining areas where the initial content of SOM is generally close to zero and soil fertility is very low (Nii-Annang et al. 2009). The increase in SOM in reclaimed areas depends on the amount of biomass production and return to soil as well as mechanisms for C protection and retention. Due to its high potential for litterfall production and nitrogen fixation, *R. pseudoacacia* improves soil physical, chemical, and biological properties by increasing SOM, thereby converting mine spoils into productive and sustainable soils (Grünwald et al. 2007).

High amounts of litterfall increase fire risk in European Mediterranean areas (Delabrazze 1986) and, therefore, the risk of C emissions to the atmosphere. Implementation of silvopasture has been shown to reduce fire risk through the enhancement of litter incorporation into the soil as nitrogen is added with the urine of the animals and C/N relationship is reduced (Etienne et al. 1996; Rigolot and Etienne 1996).

It is well known that soil management activities such as plowing or fertilization may reduce or increase SOM content. Matos et al. (2010a, b) investigated the effect of conversion from silvopasture to arable land and reported lower contents of total organic carbon (TOC) and total nitrogen (TN) in arable soils than silvopasture. The composition and distribution of SOM also differed between these two systems. The light fraction C content declined with depth in silvopasture system, while there were no such depth-related differences in arable system. This can be attributed to tillage in arable systems, which leads to the disturbance of upper soil layers causing an increase in mineralization rates, CO<sub>2</sub> emissions from soils, and the reduction of soil C. Soil management through fertilization also affects soil C storage. Mosquera-Losada et al. (2010b) reported that the addition of sewage sludge (pH around 7) in acidic soils (water pH = 4.5) increased SOM content through the input of organic matter as well as calcium via the sewage sludge (Fig. 5). The SOM content was not modified when mineral nitrogen was added, as incorporation of organic residues through the improvement of soil pH was not promoted. In a *Populus canadensis* Moench silvopastoral system developed on a Galician (Spain) acid soils with pH around 5.5, the SOM content in winter was related to pasture production in the preceding autumn ( $r^2 = 0.93$ ; % SOM = 0.48 autumn production [Mg ha<sup>-1</sup>] + 8.87  $p < 0.05$ ), which



**Fig. 5** Soil organic matter (SOM) and  $\text{pH}_{(\text{water})}$  under different fertilization treatments of *Pinus radiata* D. Don in Galicia. NF: no fertilization; N160, N320 and N480 refer to 160, 320, and 480  $\text{kg N ha}^{-1}$ , respectively; MIN: inputs of a mineral compound fertilizer 500 kg of 8N: 24 $\text{P}_2\text{O}_5$ : 16  $\text{K}_2\text{O}$ . The letters on graph indicate significance of differences between treatments at  $p=0.05$  according to Duncan's multiple range test (Source: López-Díaz et al. 2007; Rigueiro-Rodríguez et al. 2011a)

suggested that organic matter was incorporated but not mineralized (Mosquera-Losada et al. 2011a). Therefore, SOM seems to have increased when herbaceous autumn production was high, causing an increase in organic matter inputs into the soil.

It has been proposed that C stored in the soil could be linked to different soil-size fractions (Lal 2005). However, there have been only very few studies evaluating C storage in different soil-size fractions in treeless versus AFS. Carbon associated with macroaggregates (250–2,000  $\mu\text{m}$ ), microaggregates (53–250  $\mu\text{m}$ ) and silt clay (<53  $\mu\text{m}$ ) can have mean residence time of 1–10, 1–25, and 100–1,000 years, respectively (Parton et al. 1987; Schimel et al. 1994). One study carried out in Galicia, Spain, showed that the broadleaf *B. alba* sequestered more C in the 250–2,000  $\mu\text{m}$  size class as compared to soils under the conifer *P. radiata*. However, pastures had more C than pine silvopasture in soils with finer particle sizes fractions of less than 250  $\mu\text{m}$  (Howlett et al. 2011).

## Conclusion

Agroforestry systems have great potential to enhance C sequestration compared with tree-less agronomic systems, and therefore their implementation should be considered as a land use option in Europe. The limited number of studies undertaken so far at

various locations and systems in Europe have shown that the factors that contribute to higher C sequestration under AFS include greater above-and below-ground spatial heterogeneity in the vegetation (trees and crops), production of higher amounts of plant biomass, more extensive root exploration of rhizosphere and increased litterfall inputs to the soil. Further studies are needed on all these as well as other aspects of the soil and associated vegetation to evaluate different components of agroforestry systems, including trees, the understory, animals and their interactions, under specific edapho-climatic conditions. The implementation of AFS contributes to an overall sustainable land management based on the increase of soil fertility by C enrichment in humus and the potential of C sequestration in the soil–plant system.

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