REVIEW ARTICLE

Forest management and carbon sequestration in the Mediterranean region: A review

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Abstract

Aim of study: TTo review and acknowledge the value of carbon sequestration by forest management in the Mediterranean area.

Material and methods: We review the main effects of forest management by comparing the effects of silvicultural systems (even-aged *vs*. uneven-aged stands, coppice systems, agroforestry systems), silvicultural options (thinning, rotation period, species composition), afforestation, harvesting, fire impact or effects of shrub layer on carbon sequestration in the Mediterranean area.

Main results: We illustrate as forest management can clearly improve forest carbon sequestration amounts. We conclude that forest management is an effective way to maintain and enhance high carbon sequestration rates in order to cope with climate change and provision of ecosystem services. We also think that although much effort has been put into this topic research, there are still certain gaps that must be dealt with to increase our scientific knowledge and in turn transfer this knowledge to forest practitioners in order to achieve sustainable management aimed at mitigating climate change.

Research highlights: It is important to underline the importance of forests in the carbon cycle as this role can be enhanced by forest managers through sustainable forest management. The effects of different management options or disturbances can be critical as regards mitigating climate change. Understanding the effects of forest management is even more important in the Mediterranean area, given that the current high climatic variability together with historical human exploitation and disturbance events make this area more vulnerable to the effects of climate change.

Additional keywords: global carbon cycle; forest sink; forest mitigation strategies; carbon sequestration potential; climate change mitigation; Mediterranean forests. **Authors´ contributions:** Conception of the manuscript's idea and wrote the manuscript: RRP and MR. Reviewing the literature and drafting of the manuscript: RRP, ABO and MR. Critical review of the manuscript: RRP, ABO, ELS, FB and MR.

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Introduction

Carbon sequestration in forests, which perform a key role as CO_2 sinks, can help mitigate the effects of climate change. CO_2 from the atmosphere is removed by plant photosynthesis and stored as carbon in biomass. Hence, biomass and soil (from the decomposition of biomass from litterfall and rhizodeposition) are the two main forest compartments in which carbon is stored. The deadwood compartment can account for a high quantity of carbon in some forests and should also be considered, particularly as biodiversity policies encourage an increase in the amount of deadwood. In turn, this would result in greater soil carbon sequestration (Magnússon

et al., 2016), although in the case of managed forests, deadwood usually comprises small branches, twigs and stumps, with few large logs or snags (Christensen *et al.*, 2005).

The world forest carbon stock was estimated to be 861 Pg C in 2011 (Pan *et al.*, 2011), with soil to a depth of 1m being the main pool (44%), followed by biomass (42%), deadwood (8%) and litter (5%). The potential carbon sink of world forests has been addressed by several authors. For example, Pan *et al.* (2011) reported that the gross sink in established forests is 2.4 Pg C/yr and that there are tropical land use change emissions of 1.3 Pg C/yr, resulting in a net forest sink of 1.1 Pg C/yr. Other authors, such as Le Quere *et al.* (2015)

quote a figure of between 2.3 and 3.0 Pg C/yr as the net forest sink. Emissions from fossil-fuel combustion and industrial processes reached 9.7 Pg C/yr in 2015 (35.7 Pg CO_2/yr) (Olivier *et al.*, 2015), the net effect of forests being to remove 11% of the annual CO_2 emissions.

In order to increase this annual sink, forest stakeholders (managers, owners, policy makers, etc.) should improve management with the aim of expanding growth and providing better timber products such as building material or substitution of other materials. Conservation must also be promoted, reducing deforestation and degradation of forest land. This needs to be addressed in the short term since the global forested area decreased by 3.1% over the period 1990 to 2015 (FAO, 2015). However the worldwide demand for wood is increasing. The quantity of wood harvested over the period 2010-2014 has increased from 3.5 to $3.7 \cdot 10^6$ m³/yr (FAO, 2016). According to the FAO data, the forested area under management plans accounts for $2100 \cdot 10^6$ ha (taking into consideration both production and conservation functions) and certified forests cover $438 \cdot 10^6$ ha. These figures provide important indicators, revealing that sustainable forest management is being applied and that mitigation and adaptation to global change can be considered among the main objectives of forestry.

The main forestry strategies aimed at mitigating climate change (Dixon *et al.*, 1994; Nabuurs *et al.*, 2007; Canadell & Raupach, 2008; Bravo *et al.*, 2008b) are to: (i) maintain the forest area or increase it through reforestation; (ii) avoid deforestation and degradation; *III*) to maintain or increase the carbon density of existing forests; (iii) encourage the use of forest products (mainly wood products, thereby improving off-site carbon storage), promoting them as alternatives to products with high manufacturing costs, and increasing the use of bioenergy to substitute fossil fuels. These forestry strategies should be assessed within the framework of sustainable forest management (Nabuurs *et al.*, 2007). It has been observed that unmanaged forests may hold larger amounts of carbon than managed forests, depending on site conditions, forest structure, development stage, etc. Hence, some authors have suggested that old-growth forests should be left intact as they continue removing huge amounts of carbon from the atmosphere and storing into biomass and soil (Luyssaert *et al.*, 2008; Stephenson *et al.*, 2014). Harmon & Marks (2002) reported that the old-growth forest strategy was best when carbon sequestration was the only concern. Nevertheless, this strategy is discussed as it presents some disadvantages, for example it is known such forests do not fulfil the needs of society with regard to the supply of wood

products. Furthermore, die-off processes in old-growth forests would tend to reduce the balance with growth or take it towards zero. Carbon sequestration, however, is frequently not the only objective that managers must consider. They must also take into consideration all the possible ecosystem services provided by forest systems, from environmental, economic and social perspectives. As regards carbon sequestration, more benefits can be obtained from managed forests, such as higher forest growth rates, lower mortality rates, better provision of wood and non-wood forest products, enhanced stand health, or decreased risk of forest fire and therefore a reduced vulnerability to extreme climatic events. Therefore, given the benefits of forest management on stand growth and development along with the ecosystem services previously mentioned, we consider that sustainable forest management provides the most appropriate approach to addressing global change. Hence, a greater understanding of the impact of forestry on the carbon cycle is needed in order to develop and improve management strategies to mitigate climate change.

Mediterranean areas are characterized by high annual climatic variability, with hot, dry summers and irregular precipitation. Climate change scenarios point to increasing temperatures and changes in the precipitation regime in this area (Lindner & Calama, 2013). Furthermore, forests in the Mediterranean area have a long history of human exploitation. These key characteristics, together with the frequent occurrence of disturbances such as fire or pests, have influenced the composition, structure and functioning of these forest ecosystems. Hence, in order to maintain the level of ecosystem services in this area, forest management is required, particularly in the light of reports that climate change is causing a reduction in the carbon sink capacity of unmanaged Spanish forests due to lower water availability (Vayreda *et al.*, 2012).

Data regarding carbon stocks (living biomass, deadwood and soil) in this area are therefore essential. Due to the lower productivity of Mediterranean systems in comparison to other northern- or central-European ecosystems, most of the national or regional biomass carbon accounting has only recently been conducted, mainly for the development of biomass models and sampling procedures. Identifying soil carbon stocks is crucial, both with regard to mitigating the effects of climate change (carbon can be stored in the soil for years) and as a source of organic matter (indicator of soil quality). Mediterranean soils are characterized by variability of soil properties, reduced water holding capacity, shallow soil horizons, great amounts of stony materials on the soil surface, different soil processes such as carbonate loss and high risk of erosion (Rodeghiero

et al., 2011). Hence, determining the forest floor (litter) and mineral soil organic carbon stocks as well as the influence of forest management on soil carbon stocks forms a critical part of decision-making processes (Jandl *et al.*, 2007; Tonon *et al.*, 2011). Deadwood is recognized as an essential component in forest stands, particularly with regard to biodiversity conservation and ecosystem functioning, and it represents an important forest carbon pool (Rondeux *et al.*, 2012). Forest inventories provide data to estimate this carbon pool (*e.g.*, Harmon & Marks, 2002) and although deadwood estimates for Mediterranean forests are scarce, the importance of deadwood in carbon storage and the influence of forest management have gained prominence in recent years (*e.g.*, Lombardi *et al.*, 2008; Herrero *et al.*, 2010; Paletto *et al.*, 2014).

The main effects of forest management on carbon stocks usually occur in the living biomass compartment due to a reduction in stocking density as a consequence of harvesting, thinning, regeneration cuttings, etc. (D'Amato *et al.*, 2011). Stocking density reduction also affects litterfall by decreasing input after cuttings (*e.g.*, Roig *et al.*, 2005; Jiménez & Navarro, 2016). In the short-term, the soil carbon stock (particularly in the forest floor, which may receive more litter and deadwood such as logging residues from harvesting operations), might also be strongly affected by silvicultural operations as a result of soil compaction by machinery along with litter removal and mixing with the mineral soil. The new microclimatic conditions of the soil caused by opening of the canopy cover through thinning or regeneration cuttings may lead to more light/temperature on the soil surface, which may in turn modify the decomposition rate of the organic matter (*e.g.*, Montero *et al.*, 1999; Roig *et al.*, 2005; Blanco *et al.*, 2011; Bravo-Oviedo *et al.*, 2017).

Improving carbon estimation and our understanding of the effects of forest management poses important challenges but also provides opportunities for forest managers to include carbon sequestration among the different objectives pursued in the management of large areas of forest land.

The main objective of this review was to compile the most relevant information with regard to forest management strategies aimed at mitigating climate change through carbon sequestration, focusing on the Mediterranean region. Firstly, we review the effect of different management options on carbon storage, embracing different forest systems, silviculture, afforestation and the impact of disturbances. Finally, we discuss the main challenges for research on carbon sequestration in Mediterranean forests.

In order to help forest managers in making decisions as regards silviculture aimed at carbon sequestration,

the different management systems commonly employed in the Mediterranean region and their implications for carbon are presented in the first section. The second part addresses the impact of common silvicultural activities on soil carbon to determine how carbon stocks could be maximized. The effects of major disturbance events in the Mediterranean area, which managers should attempt to minimize to reduce the risk of carbon loss, are also assessed.

Silviculture system

Even-aged *vs.* uneven-aged systems

According to the silvicultural system used, the age structure of the resultant stand can vary from even- to uneven-aged. Forest stands are frequently managed as even-aged stands for economic reasons, with timber being the most important product. However, if other ecosystem services are considered such as soil protection, biodiversity conservation or non-wood forest products (cones, mushrooms, berries….), then uneven-aged stands might sometimes be more appropriate (Pukkala *et al.*, 2011; Pukkala, 2016). As regards carbon sequestration, uneven-aged systems may be the better alternative and should be taken into consideration. The main advantage of uneven-aged stands with regard to carbon stocks is that tree cover and therefore continuous litter input is always present, ensuring permanent soil and watershed protection, whereas in even-aged stands there will be periods with no soil cover or only partial soil cover, which could lead to carbon losses. Long-term studies have reported that uneven-aged forests may present higher carbon stocks than even-aged forests (*e.g.*, Powers *et al.*, 2011; Nilsen & Strand, 2013; Puhlick *et al.*, 2016). Model simulations also support these assertions. In stand simulations in Austria, Seidl *et al.* (2008) concluded that uneven-aged structures have significant potential to increase carbon storage and achieve multiple management objectives. Taylor *et al.* (2008), through a simulation which compared the management effects of clear-fellings and partial-felling systems in Canada, also found that total ecosystem carbon increased in uneven-aged stands. Similarly, based on simulations for northeastern USA, Nunery & Keeton (2010) reported the same pattern, indicating that carbon sequestration was greater in uneven-aged systems. Higher soil carbon stocks were also found by Jonard *et al.* (2017) in uneven-aged stands in France. When other management objectives (*e.g.*, timber, berries and carbon) were considered in the simulation, Pukkala *et al.* (2011) found that uneven-aged management was more profitable than even-aged plantation forestry

in Finland. This general trend, pointing to greater carbon stocks in uneven-aged structures, has also been reported for Mediterranean environments. Río *et al.* (2017), in a simulation for Stone pine stands in Spain observed that an uneven-aged structure favors the joint production of cones and timber, resulting in a higher carbon sequestration rate while maintaining a minimum carbon stock on-site, which is never extracted from the forest. This uneven-aged structure implies greater soil protection along with other advantages of particular relevance in Mediterranean systems. Although more complex structures, such as uneven-aged stands, may be more appropriate in terms of carbon sequestration, the risk of disturbances should also be taken into consideration (Jactel *et al.*, 2009). In this regard, uneven-aged structures can be more susceptible to fire, facilitating the transition from surface to crown due to the vertical continuity of fuel associated with these structures. González *et al.* (2007) reported that the degree of expected fire damage is lower in mature even-aged stands in comparison to uneven-aged stands or young even-aged stands. However, more research is required to confirm such differences between stand structures in terms of carbon sequestration, particularly as most of the examples mentioned above were obtained through forest modeling. Our understanding of the effects of structure is still limited in the case of Mediterranean areas.

Coppice systems

Although the coppice system was widely employed until the middle of the last century due to the demand for firewood and charcoal in Europe, the importance of this system began to decrease over the second half of the century. By the beginning of the XXI century, most coppice stands were no longer managed (Serrada *et al.*, 1992; Buckley & Mills, 2015). Today, coppice stands are again gaining prominence due to their potential role in the production of bioenergy, which is currently being promoted as part of a strategy to reduce emissions from fossil fuels, as well as the increasing revenues from firewood. The production of high quality wood can also be a valuable output in the case of species suited to coppice systems (ash, chestnut, oaks…). However, these systems could be enhanced through management aimed at achieving higher carbon sequestration rates while maintaining the provision of ecosystem services.

Coppice stands account for a large area. In the Mediterranean area of Europe, coppice stands cover more than $15 \cdot 10^6$ ha (Bravo-Fernández *et al.*, 2008; Stajic *et al.*, 2009), with more than $3.5 \cdot 10^6$ ha in Italy (INFC, 2005) and more than $2.2 \cdot 10^6$ ha in Spain (Bravo-Fernández *et al.*, 2008). However, due to lack

of management, coppice forests currently present the following problems of vitality and stability, as described by Bravo-Fernández *et al.* (2008): (i) The age of these forests tends to be greater than the length of their rotation period, hence, older stools may have lost their regeneration ability, (ii) sexual regeneration is scarce, (iii) stocking density is often excessive and competition is intense, leading to reduced vitality, a large accumulation of biomass and therefore a high risk of forest fire. According to these authors, strategies that should be considered in order to recover these coppice forests include conversion to high forest, conversion to coppice with standards, or maintenance of the present coppice system. Appropriate strategies are important not only as regards the conservation of these forests but also to improve the provision of ecosystem services, including fuelwood production for bioenergy purposes (Chatziphilippidis & Spyroglou, 2004; Bravo-Fernández *et al.*, 2008; Cotillas *et al.*, 2016; Mairota *et al.*, 2016).

The soil carbon pool has been identified as the main compartment in these coppice systems (Gallardo Lancho & González, 2004a,b; Makineci *et al.*, 2015), with high potential for carbon sequestration (Turrión *et al.*, 2009). However, the biomass carbon sink is also relevant, as has been evidenced in studies conducted in the Mediterranean region (*e.g.*, Montero *et al.*, 2004; Cañellas *et al.*, 2008; Cotillas *et al.*, 2016). Hence, in the Mediterranean area, coppice management for biomass production using medium rotation periods could also provide an important source of raw material for bioenergy purposes, providing an alternative to fossil fuels and therefore reducing the emissions associated with the latter (Cañellas *et al.*, 2004; Laina *et al.*, 2013; Spinelli *et al.*, 2014).

Agroforestry systems

In areas where natural pastures and shrub formations are important for livestock or for hunting, in which trees are scarce or have completely disappeared due to either natural disturbance such as fires or human activities, conversion to agroforestry systems by incorporating trees into the landscape could help to maintain the current land uses and also improve the functioning of the ecosystem. This strategy could also be employed on agricultural land, where trees could be used as windbreaks, buffers or for shade provision (Nair *et al.*, 2010). Soil fertility will be improved as a result of the increase in soil organic matter by litterfall and rhizodeposition in agroforestry systems and the employment of this strategy will also contribute to reducing soil erosion and improve water quality (Buresh & Tian, 1998; Moreno *et al.*, 2007; Jose, 2009). This

positive effect would be greater if N-fixing tree species were used. This kind of restoration could be important in dry areas, where trees can also be a source of fuelwood, fodder, fruits and/or other non-wood forest products. Carbon stocks would be higher in agroforestry systems in comparison to traditional management systems without tree species as a consequence of tree biomass growth and the resultant effect on the soil (Jose, 2009; Jose & Bardhan, 2012). The carbon sequestration rate in this system will depend on the species composition, age of the component species, geographic location, environmental factors and management practices adopted (Nerlich *et al.*, 2013) as well as on the soil type and legacy effect of historical management.

In the south of Europe, agroforestry systems offer great potential for carbon sequestration given the large area covered by these systems in the Iberian peninsula, covering more than $5.5 \cdot 10^6$ ha (Marañón, 1988). The restoration and management of the tree and shrub layers in these systems will also have a substantial effect on soils. Studies focusing on soil carbon stock distribution (Howlett *et al.*, 2011a,b; Simón *et al.*, 2013), land management (Pulido-Fernández *et al.*, 2013; Seddaiu *et al.*, 2013, López-Díaz *et al.*, 2017), fine root distribution (Moreno *et al.*, 2005) or shrub biomass (Castro & Freitas, 2009; Ruiz-Peinado *et al.*, 2013b) could help forest managers to maximize carbon sequestration, avoid degradation and guarantee sustainability.

Shrub layer importance

Shrublands account for a large part of forest land throughout the world, around $22.7 \cdot 10^6$ km^2 in total (Friedl *et al.*, 2010). In 1981, shrublands covered more than 450,000 km^2 in the Mediterranean basin (Di Castri, 1981). This area may now be greater as pastures, abandoned agricultural land and open forests are increasingly being encroached by woody species. Several factors have contributed to this situation, ranging from climate change to anthropogenic factors related to land management or disturbances (*e.g.*, Van Auken, 2000; Eldridge *et al.*, 2011) such as those associated with the reduction of agricultural cultivation on marginal land; the decrease in forest livestock; the effect of recurrent forest fires; and in some instances, as a consequence of forest management. The effect of the encroachment of woody species is positive in terms of carbon sequestration due to the increase in soil organic carbon as well as aboveground biomass (Maestre *et al.*, 2009; Eldridge *et al.*, 2011; Li *et al.*, 2016). Among other positive effects of shrub cover is the role of shrubs as nurse plants (facilitation) for the establishment of tree regeneration. In this regard

they help reduce abiotic and biotic stress during the seedling stages (Castro *et al.*, 2002; Gómez-Aparicio *et al.*, 2004). However, dense shrub layers can hamper the regeneration process due to competition which can interfere with seedling development. Shrub clearing (particularly strip clearing) can be applied in Mediterranean areas to provide space for tree regeneration, either natural or human-induced, in semiarid ecosystems (Pérez-Devesa *et al.*, 2008). This operation also serves to reduce forest fire risk or to improve pastures for livestock, although a certain level of shrub cover, which may be beneficial to improve pasture productivity (López-Díaz *et al.*, 2015) is retained. Shrubland management aimed at facilitating tree establishment and stand development, even where tree stocking density is low, can lead to increased carbon stock. This is due to the higher tree biomass growth and litter inputs to soil from litterfall and rhizodeposition, as well as to soil protection by tree canopies. In fact, the soil carbon stock under the adult tree canopy can be double that of areas with lower tree incidence (Howlett *et al.*, 2011a; Rossetti *et al.*, 2015).

The carbon stock associated with shrubs is frequently neglected, even though it could play an important role as a carbon sink (Daryanto *et al.*, 2013). An increasing amount of research in recent years has been focused on estimating the carbon stocks in Mediterranean shrublands, mainly through the development of estimation tools (*e.g.*, Navarro & Blanco, 2006; Corona *et al.*, 2012; Ruiz-Peinado *et al.*, 2013b; Botequim *et al.*, 2014; Pasalodos-Tato *et al.*, 2015). The importance of shrub layer will depend on the ecosystem considered, the shrub species and tree density among other factors. For example, in a *Pinus sylvestris* L. stand in Central Spain, the mean shrub carbon stock was between 1-2% of the total aboveground carbon biomass (García del Barrio, 2000). However, in open woodlands of *Quercus ilex* L. (dehesas in western Spain), because of the lesser magnitude of the tree layer, the contribution of the shrub layer to the total biomass carbon stock ranges from 20% to 29% (Ruiz-Peinado *et al.*, 2013b).

In Spain, shrublands account for $11 \cdot 10^6$ ha of forest area, more than $7.8 \cdot 10^6$ ha of which is either treeless or with a scattering of trees (San Miguel *et al.*, 2008). National carbon estimations for Spanish shrublands have been conducted by Montero *et al.* (2016) using models for different shrub associations (Pasalodos-Tato *et al.*, 2015). The results suggest that aboveground shrub biomass accounts for more than 91 Tg C. This figure represents 8.2% of the tree carbon stock in Spanish forests (Montero & Serrada, 2013), highlighting the importance of including shrubland in carbon accounts. The shrub layer in the Mediterranean

Table 1. Effect of thinning on carbon sequestration based on several long-term studies.

Species (stand origin)	Thinning grade[1]	Stand age	Biomass	Soil[2]	C off-site	Total C stock	Reference
					(Mg C/ha)		
Picea abies (planted)	Unthinned	58	185.2	87.9	nc	273.1	Skovsgaard *et al.* (2006)
	Thinning B		161.1	91.1	nc	252.2	
	Thinning C		135.1	89.3	nc	224.4	
	Thinning D		94.7	90.1	nc	184.8	
Picea abies (planted)	N2070	50	112.6	114.2[3]	nc	226.8	Nilsen & Strand (2008)
	N1100		90.4	118.4[3]	nc	208.8	
	N820		86.6	108.8[3]	nc	195.4	
Pinus pinaster (planted)	Unthinned	59	196.9	120.5	6.7	324.1	Ruiz-Peinado *et al.* (2013a)
	Thinning D		139.3	117.2	56.2	312.7	
	Thinning E		126.8	107.6	68.5	302.9	
Pinus sylvestris (planted)	Unthinned	52	206.8	105.6	3.1	315.5	Ruiz-Peinado *et al.* (2016)
	Thinning D		164.0	106.6	33.7	304.3	
	Thinning E		148.8	102.1	43.9	294.8	
Pinus sylvestris (natural)	Unthinned	90	129.2	149.1	19.4	297.7	Bravo-Oviedo *et al.* (2015)
	Thinning C		106.0	135.6	36.6	284.2	
	Thinning D		93.3	153.2	48.2	301.8	

[1] Thinning grade intensities are explained in each reference. [2] Soil: Forest floor+ Mineral soil 0-30 cm. [3] Soil carbon stock until a 1-m depth. *nc*: off-site carbon stock was not reported by the authors

area is also highly important with regard to soil conservation which, in turn, is also vital to carbon sequestration and to the nutrient cycle, thereby improving the sink capacity of the system.

Silvicultural options

Thinning

Although thinning will result in lower carbon storage on-site in comparison with unthinned stands due to a reduction in the number of trees and therefore the litterfall input, thinning is essential to achieve certain forest management objectives, particularly as regards controlling species composition, improving the health of the stand and obtaining production in the early stages. Furthermore, thinning leads to increased tree size and therefore value of future products (Río, 1999). When harvested products (off-site carbon) are taken into account, the total carbon stock of thinned stands is greater or at least similar to that of unthinned stands, with the economic advantage that some of the carbon is stored outside the forest as wood products. It could also be an appropriate strategy in areas where there is

significant risk of forest disturbances (fire, pests and diseases, windstorms, droughts, etc.). Moreover, carbon stocks under heavier thinning regimes have been found to be similar to those of lighter regimes (Powers *et al.*, 2011; Ruiz-Peinado *et al.*, 2013a; 2016; Bravo-Oviedo *et al.*, 2015). From a management perspective, this implies greater flexibility, allowing the forest manager to put greater emphasis on other environmental services. In the Mediterranean area of Spain, using inventory data from long term experimental plots belonging to the Spanish Forest Research Center (INIA-CIFOR) and biomass equations for P. *sylvestris* (Ruiz-Peinado *et al.*, 2011), it was concluded that lightly-thinned stands had higher on-site carbon biomass stocks (151 Mg C/ha) than either unthinned stands (145 Mg C/ha) or heavily thinned stands (116 Mg C/ha) (Fig. 1). When the off-site carbon stock (harvested biomass) is included in this balance, managed stands always present higher accumulated carbon stocks. Lightly- thinned stands reached 181 Mg C/ha, heavily thinned stands 174 Mg C/ha while unthinned stands were found to have 161 Mg C/ha. The loss of production in heavily thinned *P. sylvestris* in comparison with lightly thinned stands has previously been reported across Europe, both in terms of volume production (*e.g.*, Mäkinen & Isomäki,
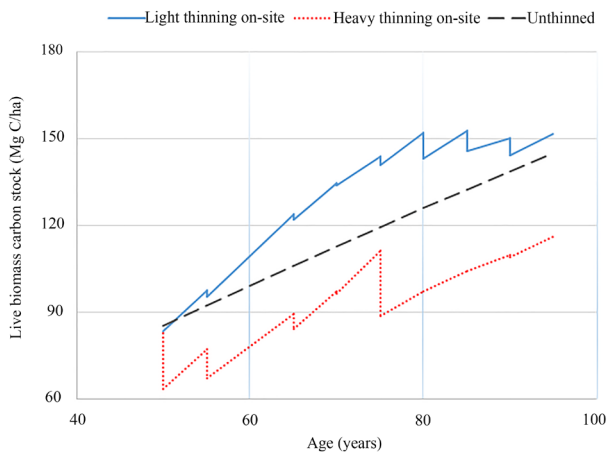
Figure 1. Effect of forest management on live biomass carbon stock in low quality sites of *Pinus sylvestris* stands in Central Spain for different thinning regimes.

2004; Río *et al.*, 2008b) and of carbon stocks in the Mediterranean region (Bravo-Oviedo *et al.*, 2015; Ruiz-Peinado *et al.*, 2016).

Although addressing carbon sequestration issues was not envisaged when the long-term experiments were established, these trials contribute valuable information in terms of identifying trends, providing pertinent information for planning purposes (Table 1).

Regarding the distribution of carbon in different forest compartments, empirical studies focused on thinning and conducted in the Mediterranean area for *Pinus pinaster* Ait. (Ruiz-Peinado *et al.*, 2013a) and *P. sylvestris* stands (Bravo-Oviedo *et al.*, 2015; Ruiz-Peinado *et al.*, 2016) found that on-site biomass carbon stocks were higher in unmanaged stands and decreased as the thinning intensity increased. The amount of deadwood was higher in unmanaged forests when a whole-tree harvesting method was applied and was lower when stem-only harvesting was used. Forest floor carbon stocks generally showed a decreasing trend as the thinning intensity increased, although differences were not statistically significant. These authors also found no differences between thinning intensities as regards the mineral soil carbon stock.

Besides the thinning intensity, the type of thinning also affects the carbon sequestration rates and mean residence time of the products. Thinning from below presented the highest carbon sequestration rate, while mixed thinning and thinning from above resulted in lower carbon storage rates than in unthinned stands (Hoover & Stout, 2007; D'Amato *et al.*, 2011). However, the products obtained using the latter type of thinning presented the longest lifespan (long-lived wood products) due to the greater dimensions of the wood

harvested in the intermediate cuttings. Nevertheless, the products obtained at the final harvest might be of smaller size than those obtained where thinning from below is employed, which could affect the lifespan of the product and the substitution effect (avoiding carbon fossil fuel emissions). Hence, thinning regimes and product lifespan should be taken into account in order to determine the most suitable forest management for carbon sequestration (Perez-García *et al.*, 2007; Fortin *et al.*, 2012; Prada *et al.*, 2016).

Simulation of thinning regimes has been developed to evaluate carbon sequestration in the biomass compartment. Garcia-Gonzalo *et al.* (2007), using a modeling approach, found that an increase in the thinning intensity also led to an increase in the total carbon stock, the pattern being similar for the different species considered. Scenarios in which no thinning was performed always showed the highest amounts of carbon as the carbon stock was mainly in the standing tree biomass. However, the lack of intermediate cuttings resulted in a temporary absence of wood products. Río *et al.* (2008a), using a growth model to compare different thinning regimes (simulations), found that in the case of Mediterranean maritime pine (*P. pinaster*) in central Spain (rotation period of 80 years), the best carbon sequestration strategy was to adopt an early (20 years), heavy thinning regime. However the opposite tendency has also been reported. For example, Balboa-Murias *et al.* (2006) found the highest biomass stocks under light thinning regimes (rotation period 30 years) in the case of maritime pine plantations on the Atlantic coast of Spain when the harvested wood is used for chipboard or panelboard. Coletta *et al.* (2016) also observed that for Douglas-fir plantations in Italy, a selective light thinning regime was the best treatment (rotation period 30 years) in terms of biomass carbon stock, without taking into account the harvested biomass. Under other simulations for *P. pinaster* in Spain (rotation period of 80 years), using a hybrid modeling approach with different climate predictions, Río *et al.* (2017) obtained the same pattern (heavy thinning regime) for the reference climate (current mean climate) as well as under a climate change scenario (+ 1.1 ºC annual temperature and -2% annual precipitation).

If the productivity of the stand is not very high, as is often the case in Mediterranean areas, timber production may not be the main management objective of the stand. Although thinning should be performed in order to improve stand conditions (fire risk reduction, avoiding growth stagnation, etc.), thinning may also be appropriate where biomass is grown for bioenergy purposes since the use of biomass in energy production would lead to a reduction in fossil fuel emissions.

Carbon losses in forests resulting from episodes of extreme heat and drought have been widely documented. The severe heat and drought that occurred in Europe in 2003 led to a 30% reduction in gross primary productivity and net carbon source of 0.5 Pg C/yr (Ciais *et al.*, 2005). The same pattern was reported for drought episodes in the Amazon region in 2005 and 2010 (Phillips *et al.*, 2009; Feldpausch *et al.*, 2016). These carbon losses reflect a decline in tree growth, reduction in net primary production and tree mortality (Ma *et al.*, 2012). Thinning to increase drought tolerance is considered a short-term adaptation strategy in the face of climate change, as stocking reduction will lead to increased soil water availability per tree in comparison to unthinned stands (D'Amato *et al.*, 2013; Bradford & Bell, 2017). As thinning from below will focus growth on the stronger, remaining trees, mortality will decrease and carbon stocks will be maintained and/or increase. Sohn *et al.* (2016) in a meta-analysis reported that thinned stands maintained higher growth levels before, during and after drought events and that the benefits increased with thinning intensity. These authors also reported that the benefits of thinning decreased with time the elapsed since the treatment was performed. These important findings are supported by recent studies in Mediterranean areas in which authors report that thinning enhances drought tolerance, with thinned stands showing higher growth than unthinned stands (Fernández-de-Uña *et al.*, 2015; Aldea *et al.*, 2017). The results obtained by Ruiz-Benito *et al.* (2013) also point to thinning as a suitable climate change adaptation strategy, leading to lower tree mortality. The trade-offs between mitigation and adaptation could be of particular importance in Mediterranean areas. For example, heavy thinning leads to greater water availability per tree but could reduce carbon sequestration rates. Conversely, light thinning maintains high carbon stocks in-situ but may increase their vulnerability in areas with high risk of disturbance (D'Amato *et al.*, 2011).

Rotation period

Extending the rotation period has been identified as a suitable management approach with regard to carbon storage both for tree biomass and soil carbon (Liski *et al.*, 2001; Bravo *et al.*, 2008a; Sohngen & Brown, 2008; Roberge *et al.*, 2016). Optimal rotations have traditionally been defined by economic objectives, subject to temporal burdens, neglecting the potential that mature stands still possess in terms of tree growth. Litter production could also be greater beyond the rotation period, which would have a positive influence on the soil carbon stock. Furthermore, the products obtained using a longer rotation would be of larger dimensions;

hence, carbon could be stored in manufactured products with a longer lifespan. However, if the rotation period were prolonged excessively, the decrease in net primary production, along with an increase in the mortality rate, could offset the abovementioned beneficial effects. Another risk associated with a longer rotation period is that timber rot may attack certain trees, such as the Mediterranean species *Phellinus pini* (Brot.) Bondartsev and Singer attacks *Pinus pinea* L. (García-Güemes & Montero, 1998), leading to a loss in the value of the wood. Certain net carbon effects cited in the literature are presented in Table 2.

Longer rotation lengths have been simulated using models such as CO2fix (Nabuurs & Schelhass, 2002; Masera *et al.*, 2003), which have pointed to the effectiveness of this strategy in achieving higher amounts of carbon (*e.g.*, Kaipainen *et al.*, 2004; Kaul *et al.*, 2010; Nizami *et al.*, 2014; Prada *et al.*, 2016). However, the existing literature on this subject contains scarce real examples of extended rotation periods, which would be necessary to confirm the model predictions. For example, Moreno-Fernández *et al.* (2015) studied a chronosequence in two Scots pine stands in a Mediterranean mountain area where regeneration is achieved using the shelterwood system. Thinning intensities were similar between stands, but there were distinct rotations periods due to differences in the regeneration system (for more details see the cited paper). One of the main conclusions of the authors was that longer rotation periods were more advantageous as regards carbon sequestration. In addition, they highlight the role of longer rotation periods to improve structural biodiversity, achieve natural regeneration and lower the susceptibility to drought.

Shorter rotation periods could also be considered which approximate the age of the maximum mean annual increment in order to maximize biomass productivity and biomass carbon sequestration. However, longer rotations yielded a higher proportion of stem carbon storage (Bravo *et al.*, 2008a, 2017; Tonon *et al.*, 2011). Thus, wood products with longer lifespans may result from longer rotations, which is of particular importance for off-site carbon storage.

Species composition

Silvicultural techniques could be used to convert existing stands to more suitable stand compositions, which may imply changing the main species or mixtures as a strategy to increase carbon sequestration as well as to mitigate and adapt to the effects of global change. In the same way, forest managers can also select the most appropriate combination of species in plantations with this objective in mind.

Table 2. Effects of extending the rotation period in different species.

Reference	Species	Extending length period proposed (rotation period)	Long-term effect (% C/ha or Mg C/ha)
Liski *et al.* (2001)	coniferous *Pinus sylvestris* *Picea abies*	+ 30 years (from 90 to 120 in Finland) (from 90 to 120 in Finland)	 Total C increases Total C decreases
Kaipainen *et al.* (2004)	pine *Pinus sylvestris* *Pinus pinaster*	+ 20 years (from 90 to 110 in Finland) (from 120 to 140 in Germany) (from 100 to 120 in Spain) (from 80 to 100)	+ 6-13% C/ha
Kaipainen *et al.* (2004)	spruce *Picea abies* *Picea sitchensis*	+ 20 years (from 90 to 110 in Finland) (from 100 to 120 in Germany) (from 40 to 60 in UK)	+ 14-37% C/ha
Bravo *et al.* (2008a)	*Pinus sylvestris* *Pinus pinaster*	+ ~40-50 years (from 70-80 to 120-140 in Spain) + ~50 years (from 80-100 to 130-150 in Spain)	+ 13-42% C/ha + 22-28% C/ha
González-Benecke *et al.* (2010)	*Pinus elliotti*	+ 13 years (from 22 to 35 in USA)	+ 21-28 Mg C/ha
Kaul *et al.* (2010)	*Shorea robusta*	+ 30 years (from 120 to 150 in India)	+ 18% C/ha
Nizami *et al.* (2014)	*Hevea brasilensis*	+ 5 years (from 35 to 40 in China)	
González-Benecke *et al.* (2015)	*Pinus pallustris*	+ 25 years (from 75 to 100 in USA)	+ 10 Mg C/ha
Prada *et al.* (2016)	*Castanea sativa*	+ 20 years (from 40 to 60 in Spain)	+ 10% C/ha

Few studies have focused on the importance of the species admixture in carbon sequestration (e.g., Gamfeldt *et al.*, 2013; Ruiz-Benito *et al.*, 2014), although some have addressed the increase in stand productivity in mixed stands (e.g., Forrester *et al.*, 2006; Pretzsch *et al.*, 2013, 2015; Liang *et al.*, 2016). Therefore, we might hypothesize that the carbon stock in living biomass in mixed stands of complementary species will also be higher than in monocultures. Higher productivity in mixed stands as opposed to monospecific stands has also been reported for Mediterranean forests (e.g., Río & Sterba, 2009; Nunes *et al.*, 2013; Riofrío *et al.*, 2017), although it is important to state that the effect of mixing on productivity varies with stand development stage, stand density and site conditions (Forrester, 2014). A less known effect of mixing, which is important to consider in the context of carbon sequestration, is its effect on wood quality (Pretzsch & Rais, 2016), which can have a significant influence on the lifespan of off-site carbon stocks.

Tree species richness has an impact on soil carbon stock through litter quality, nitrogen fixation and rooting pattern, as well as on the water balance, soil microclimate and nutrient availability (Böttcher & Lindner, 2010). Gamfeldt *et al.* (2013) concluded that soil carbon storage in organic soil (forest floor) increased with tree species richness. The results of a study by Dawud *et al.* (2016) revealed that forests with greater diversity had higher soil carbon stocks in samples taken from deeper layers (from 20 to 40 cm depth), which may be related to the stratification of roots of different tree species (niche complementarity).

A review of the existing literature suggests that the impact on forest floor or mineral soil depends on the identity of the species, species richness and typology of the admixture. Díaz-Pinés *et al.* (2011) observed that forest floor in Mediterranean mixed stands of Scots pine and Pyrenean oak (Quercus pyrenaica Willd.) presented intermediate soil carbon stocks between pure pine (highest) and pure oak stands (lowest). However,

as regards mineral soil, they found no differences between pinewoods and mixtures (oak stands had lower carbon stocks). González-González *et al.* (2012) found that mixtures with *Q. ilex* (Holm oak) in Spain showed lower soil carbon stocks than pure stands, although the differences were not statistically significant. Cavard *et al.* (2010) found that the mixture effect can be unfavorable when two species are mixed in a highly competitive environment (competing at the same level for the light, water and nutrient resources) in the absence of complementarity. Forrester *et al.* (2013) found that soil organic carbon in mixed plantations of *Eucalyptus* and N-fixing *Acacia* in Australia was higher than in pure plantations due to the increase in productivity resulting from the inclusion of the latter species.

Harvesting operations

Harvesting operations modify the stand conditions since biomass, and therefore stored carbon, is removed from the forest. During these processes, the soil is also affected as the forest floor and mineral top layer may be mixed by the machinery used in harvesting. Compaction processes could also affect the mineral soil depending on the harvesting intensity and the type of machinery employed (*e.g.*, Ampoorter *et al.*, 2012; Cambi *et al.*, 2015). Tree cover reduction and the effects of harvesting on the soil could lead to soil erosion. As previously mentioned, decreasing tree cover will reduce litterfall, although there may be an accumulation of logging residue at the time of harvesting. The soil microclimate will also be affected as more radiation reaches the soil, photodegradation being one of the main drivers of litter decomposition and leading to a possible increase in soil temperature and reduced moisture. In turn, these effects could have a notable influence on the decomposition rate of organic matter, with an intensification of decomposition in moist climates (Son *et al.*, 2004; Kunhamu *et al.*, 2009) although the opposite could occur in drier climates (Blanco *et al.*, 2011; Lado-Monserrat *et al.*, 2015; Bravo-Oviedo *et al.*, 2017). All these processes can modify soil carbon content and this can be especially significant in the case of the forest floor. The meta-analysis conducted by Nave *et al.* (2010) found that harvesting (in general) involves a small reduction (-8%) in total soil carbon stock. But the effects were different depending on the considered compartment: a considerable reduction was found for the forest floor carbon stock (-30%) and no significant effects were reported for mineral soil carbon stock. The same general tendency was reported by James & Harrison (2016) with a mean soil carbon stock reduction of 14.4%.

Harvesting methods influence the soil carbon stock in several ways depending on the residue management approach employed. Johnson & Curtis (2001) reported that whole-tree harvesting resulted in slight decreases in soil organic carbon stock (-6%) while sawlog harvesting increases (18%) the soil carbon stock in the *A* horizon. Achat *et al.* (2015) stated that conventional harvesting of tree stems (sawlog) reduced the forest floor carbon stock by 22% in comparison to unharvested stands, but no effects were found in the mineral soil organic carbon stock. When intensive harvesting was considered (whole-tree harvesting), the forest floor carbon stock was reduced by 37% and mineral soil carbon stock was mainly affected in the deeper layers (-7%).

Some of the abovementioned processes in forest soils will vary according to the climate. Hence, specific studies focusing on Mediterranean areas are required to determine the impact of harvesting on carbon stocks. Such studies could help to enhance our understanding of the carbon and nutrient cycle in these areas and allow policy makers to develop sustainable management policies (*e.g.*, Blanco *et al.*, 2005; Merino *et al.*, 2008; Ruiz-Peinado *et al.*, 2013a; 2016; Bravo-Oviedo *et al.*, 2015). Special care must be taken under fast-growing species with intensive harvesting as productivity could be negatively affected in the long term (Merino *et al.*, 1998; 2005; Edeso *et al.*, 1999; Gartzia-Bengoetxea *et al.*, 2009).

Fires

Two main types of forest fires exist: wildfires and prescribed or controlled burnings (Certini, 2005). According to this author, wildfires are very severe fires with low recurrence and which affect all fuel loads. Prescribed burnings are low severity, standard operations to decrease fuel levels and which can be applied with high frequency. These prescribed burnings affect mainly forest floor or slash, with the main objective of reducing the extent and severity of wildfires.

In the Mediterranean area, wildfires are the most important disturbance agents and fire risk has to be taken into account in forest management. Hence, prescribed fires could be used to reduce wildfire risk by decreasing fuel load. In this area, many species show adaptation strategies to the fire regime in order to increase their resilience to this disturbance: resprouting, serotiny, fire-stimulated germination, enhanced flammability, thick bark, etc. (*e.g.*, Keely *et al.*, 2011; Pausas, 2015).

Wildfires

Although the most evident impact of wildfires on forest carbon stocks is the total or partial loss of

aboveground biomass, in terms of long-term carbon sequestration in stable compartments, litter and soil organic carbon are severely affected by fires. The overall effect of wildfires on soil organic carbon stock depends on factors such as fire intensity (energy release), severity (impact on ecosystem components) and soil characteristics (porosity, moisture, etc.). In this regard, Johnson & Curtis (2001) reported no significant overall impact of fires in *A* horizons or whole soils. They also found that there was an increase in soil carbon stocks where fires had occurred more than 10 years previously, which could reflect the incorporation of unburnt residues; the transformation of fresh materials to more recalcitrant forms; the emergence of N-fixing species that enhance soil carbon sequestration or a decline in the mineralization rate (Certini, 2005). In contrast, a meta-analysis by Nave *et al.* (2011) found that wildfires in temperate forests led to a mean reduction in soil carbon stock of 35% and it was estimated that the recovery period could be between 100 and 130 years. These authors also observed that the impact of fire on soil carbon stock differs according to the soil layer considered, with a carbon stock reduction of 59% in the forest floor and no significant decline in the mineral soil.

In the case of Mediterranean ecosystems, Caon *et al.* (2014) stated that, as a general pattern, the forest floor carbon stock was reduced after wildfire and the mineral soil carbon stock declined in the short-term as well as long-term. The severe impact of fire on the forest floor is clearly the result of almost all the fresh litterfall material being burned. However, as regards the first layer of mineral soil, some studies have reported higher carbon stocks in burned areas in comparison to unburned areas, although differences are often not significant (Certini *et al.*, 2011; Santana *et al.*, 2016). Different impacts of wildfires as regards forest floor and mineral soil concentration and stock are shown in Table 3.

To maintain or recover soil carbon stocks, forestry strategies should firstly focus on minimizing the risk of wildfire and secondly, if a wildfire has already occurred, on restoring the forest cover in order to maintain and recover soil carbon stocks. In Mediterranean areas, carbon loss from mineral soil could be severe in the post-fire period due to soil erosion as the tree layer and forest floor could be greatly reduced (Novara *et al.*, 2011; Caon *et al.*, 2014).

Forest managers must take into account the wildfire risk, bearing in mind that the fire regime in the Mediterranean Basin has changed over the last 50 years with an increase in frequency and especially in size (Pausas & Fernández-Muñoz, 2012). Therefore, fire-smart forest management could involve changes to rotation lengths as well as to the timings and intensity of thinning treatments (González-Olabarría *et al.*, 2008; García-Gonzalo *et al.*, 2014) together with the removal of surface fuels through prescribed burning or the use of mechanical tools.

Table 3. Tendencies in soil carbon stock and content in Mediterranean forests and shrublands after fire.

Fire type	Reference	Forest floor C stock	Mineral soil C stock	Mineral soil C concentration
Wildfires	Hernández *et al.* (1997)			↓
	González-Pérez *et al.* (2004)			↑
	Tinoco *et al.* (2006)			↓
	Certini *et al.* (2011)	↓	NE (↑)	NE
	Vergnoux *et al.* (2011)			NE (↓)
	Rovira *et al.* (2012)			↓
	Badía *et al.* (2014)			NE (long-term)
	Caon *et al.* (2014)			↓ (long-term)
	Santana *et al.* (2016)	↓	↑	↑
Prescribed burnings	De Marco *et al.* (2005)			↑
	Campo *et al.* (2008)			NE
	Granged *et al.* (2011)			↓
	Meira-Castro *et al.* (2015)			NE
	Alcañiz *et al.* (2016)			NE (long-term)
	Armas-Herrera *et al.* (2016)			↓

↑ soil carbon stock/concentration increased; ↓ soil carbon stock/concentration decreased; NE: no significant effect with tendency in brackets if reported.

Prescribed burnings

As described above, prescribed burning is a valuable forest management tool used to reduce fire risk by decreasing fuel load. The effects of prescribed fires on soil carbon stocks vary considerably, although the impact is generally lower than that of wildfires. These effects will depend on frequency and severity, due to the limited soil heating and the protective effect of the remaining surface cover (Fernandes *et al.*, 2013). As regards differences between low or high frequency fire occurrence, Benett *et al.* (2014) identified a slight, although not significant, decreasing tendency in soil carbon stocks both for forest floor and mineral soil to a 30-cm depth. The interval between prescribed fires should be as long as possible in order to minimize the potential carbon loss associated with high fire frequency regimes. Temporary effects on soil carbon stocks may be observed after a prescribed fire. In a study conducted in a Mediterranean forest, Alcañiz *et al.* (2016) found an increase in the carbon concentration one year after the fire and then a progressive decrease over time to lower values than those registered previous to the fire, although differences were not statistically significant. Other studies of prescribed burning in Mediterranean areas which describe tendencies in soil carbon stock are presented in Table 3.

The severity of prescribed burning should also be taken into account as regards carbon stocks. Less severe fires should be established as the most sustainable regime (Fernandes *et al.*, 2013) in order to maintain the soil carbon stocks as high as possible. There may also be a notable loss of carbon through soil erosion following a prescribed fire, reaching similar levels to those of direct carbon loss through fire.

Although the use of mechanical tools both to reduce the fuel load and use of wood chips for energy purposes may be preferred to prescribed burning (Madrigal *et al.*, 2017), the latter is a more cost-effective operation (Fernandes *et al.*, 2013) which could also have a positive influence on tree growth as long as it is of low intensity (Valor *et al.*, 2013).

Afforestation

Even in the Mediterranean area where productivity is not particularly high, afforestation offers a high potential for carbon sequestration as tree biomass develops quickly, rapidly exceeding that of areas with no afforestation or that of natural stand development. The effects on soil carbon stocks are also significant (*e.g.*, Novara *et al.*, 2012; Pérez-Cruzado *et al.*, 2012), with mean ratios of mineral soil carbon sequestration of 0.46 Mg C/ha·yr in temperate areas for land-use change from cropland to forest (0.80 Mg C/ha·yr including forest floor and mineral soil) (Poeplau *et al.*, 2011). However, soil carbon sequestration processes are very slow and changes are difficult to determinate in the short-term due to the high spatial variability. Soil preparation techniques could also cause a temporary reduction in soil carbon stock in the short- or medium-term and the net effects on the soil of afforestation may be delayed due to the mixing of forest floor and mineral soil along with the exposure of the latter, which leads to an increase in decomposition rates (Jandl *et al.*, 2007). Carbon losses are higher as the intensity of the soil disturbance increases (*e.g.*, Johansson, 1994; Gartzia-Bengoetxea *et al.*, 2011; Fonseca *et al.*, 2014; Wang *et al.*, 2016). Intense soil preparation techniques, *e.g.* mechanical terracing, which has been used in some areas of Spain, is not thought to increase soil organic carbon (Garcia-Franco *et al.*, 2014). Segura *et al.* (2016) compared different soil-preparation techniques at a semi-arid site, reporting that they had a similar effect on carbon stocks in the medium-term. These authors suggest that because both soil carbon dynamics and input of organic matter take place very slowly in Mediterranean areas, evidence of changes may be difficult to detect in the short or medium-term. Hence, any increase in soil organic carbon stocks resulting from litter inputs and soil protection may only become apparent after a long time period (Fernández-Ondoño *et al.*, 2010).

The main improvement in soil carbon sequestration and soil fertility (Jandl *et al.*, 2007) associated with afforestation results from increased litterfall and rhizodeposition inputs, improved soil protection due to the soil cover, greater nutrient availability and increased water-retention capacity (*e.g.*, Fernández-Ondoño *et al.*, 2010; Tesfaye *et al.*, 2016). The amounts of soil carbon sequestered will depend on the species used (*e.g.*, Pérez-Cruzado *et al.*, 2012; Vesterdal *et al.*, 2013; Gómez de la Bárcena *et al.*, 2014). The use of N-fixing species could provide an optimal strategy as these species stimulate the humification of the litter, increasing the soil carbon sequestration (Prescott, 2010).

The previous land use, as previously mentioned, is considered the main factor when assessing soil carbon pools as this is the reference level for accounting soil carbon stock. According to results of a study by Laganière *et al.* (2010), afforestation in croplands results in a mean increase of 26% in soil organic carbon stocks, with slight improvements in pastures (3%) and natural grasslands (9%), although not statistically different from zero. These authors also support the observation that clay soils have a greater carbon storage potential (+25%) than coarse-textured soils.

Table 4. Main effects (both positive and negative) of forest management on forest carbon stocks in the Mediterranean area.

Decision about	Treatment	Advantages	Handicaps
Structure	Even-aged	Simple management	Stages with reduced or no soil cover that could finish in soil erosion, increase in decomposition rates of organic matter and soil carbon stock reduction
	Uneven-aged	Higher carbon stocks (Observed & Modelled) than even-aged stand Soil protection (higher soil carbon stock)	Complex management Higher forest fire risk (vertical canopy structure)
	Coppice systems	Recovery of coppice systems (now mainly unmanaged) Firewood production (bioenergy)	Intensive management could reduce soil carbon and nutrient stocks
	Agroforestry systems	Incorporation of a tree layer (multiple products) Higher carbon stocks	Complex management
	Shrub layer	Higher carbon stocks (biomass and soil) Soil cover (reduced erosion) Tree regeneration could be enhanced (nurse effect)	Higher forest fire risk (more biomass and continuous structure) Tree regeneration could be difficult to obtain (competition processes)
Stocking reduction	Unthinned	Higher carbon stock on-site	Higher carbon stocks on-site could not be a good strategy in areas with high risk of disturbances
	Thinned	Carbon storage off-site Flexibility of thinning intensities for carbon storage No significant effect in forest floor and mineral soil carbon stock in medium-long rotations	Intensive management could reduce soil carbon and nutrient stocks
Rotation period	Extending rotation period	Higher biomass and soil carbon stocks Higher sizes of wood products Enhancement of biodiversity	Higher risk of timber rot attacks
	Shorter rotation period	Maximum annual carbon increment	Wood products are not showing the maximum lifespan
Species composition	Pure stands	Simple management	Higher fire risk or disturbance effects
	Mixed stands	Higher productivity in case of complementary species More diverse ecosystem services (adaptation to climate change) Higher impact of species richness in soil carbon stock Soil carbon stock depends on species identity	Complex management
Harvesting		Wood products Competition control Reduction of fire risk (on-site carbon protection)	Reduced litter inputs and soil cover Potential increase of decomposition rates Compaction could impact soil carbon storage
Fires	Wildfires		Aboveground biomass losses (total or partial) A general reduction of soil carbon stocks
	Prescribed burning	Planned reduction of fire risk (by biomass reduction) Complex management	Partial reduction of aboveground biomass and forest floor (depends on fire intensity) Temporal effect on soil carbon stock (reduction)
Afforestation		Improve in biomass and soil carbon stock (depending on previous land use) Improve on soil fertility (higher litterfall inputs, depending on previous land use)	Soil carbon sequestration is a very slow process in poor soils under Mediterranean climate Site preparation techniques could impact soil carbon stocks

Furthermore, the tree species planted is important; the soil carbon stock increments approximating 25% when broadleaf species are employed whereas the percentage drops to 12% in the case of *Pinus* spp. or *Eucalyptus* spp. However, processes that stabilize carbon in soils are slow, perhaps taking more than a century. Therefore, any increment may not be detected in the short or medium-term (Poeplau *et al.*, 2011). Their results revealed that in the temperate area, afforestation of croplands led to an increase of 22% in the soil carbon stock in the first 20 years and 117% after 100 years, considering forest floor and mineral soil to a depth of 30 cm. These authors reported that almost 30% of this stock is present in the forest floor in a labile form that could be affected by disturbances. Conversion of grassland to forest resulted in a reduction of 4% in the soil carbon stock 20 years after the afforestation. Additionally, they reported that the soil carbon stock could be temporarily reduced in the short- or medium-term due to the soil preparation techniques (as it has been mentioned in a previous section), with an increase of 30% after 100 years (including forest floor), mainly due to the forest floor carbon accumulation. Nave *et al.* (2013) reported that afforestation increases soil carbon stocks by 21% and that this increase can be observed between 15 and 30 years after the afforestation. This time span may not be sufficient in arid or semi-arid areas in the Mediterranean region due to the poor soil conditions and slow soil dynamics under this climate. Hence, soil organic carbon stocks in a semi-arid area under a different land use may not differ significantly (Albaladejo *et al.*, 2013).

Perspectives and challenges

Carbon sequestration potential and human intervention in forests was identified as a research priority at the beginning of this century for Mediterranean forests (Scarascia-Mugnozza *et al.*, 2000). An important research effort has been undertaken over the last decade to improve forest carbon estimations and to determine the effects of management on carbon sequestration in the Mediterranean area, as described this review and summarized in Table 4. Most of this research has been done in the northern and western areas of the Mediterranean region, but more research along these lines is currently in progress in southern and eastern areas (*e.g.*, Durkaya *et al.*, 2013; Makineci *et al.*, 2015; Oubrahim *et al.*, 2015; Zribi *et al.*, 2016). In spite of this effort, there are still certain gaps in our knowledge that need to be addressed in order to fulfill the requirements of our society. Most of these gaps in our knowledge are not specific to Mediterranean forests,

such as the need for better estimation of belowground biomass or the need to develop biomass equations for mixed forests. Others, however, are more pronounced in this region, such as the role of afforestations for carbon sequestration.

Many of the studies focusing on different management alternatives, such as extending rotation period, different age structures or thinning schedules, have been based on forest model simulations (*e.g.*, Liski *et al.*, 2001; Bravo *et al.*, 2008a; Rio *et al.*, 2017). Although this approach can help to identify the best management alternatives in terms of carbon accounts, empirical studies which consider all forest carbon compartments are needed to test the simulation results. This fact is even more patent for Mediterranean forest, since there are scarce empirical studies dealing with management alternatives (*e.g.*, de las Heras *et al.*, 2013; Ruiz-Peinado *et al.*, 2013a; 2016; Bravo-Oviedo *et al.*, 2015). For instance, only a few studies have addressed the effect of silvicultural treatments on carbon sequestration in Mediterranean coppices (*e.g.*, López-Serrano *et al.*, 2010; Makineci *et al.*, 2015) or the effect of longer rotation periods in this area (Bravo *et al.*, 2008a; Moreno-Fernández *et al.*, 2015).

Mixed forests display huge potential benefits in terms of ecosystem services (depending on site and species) so interest in this kind of forest is currently increasing (Bravo-Oviedo *et al.*, 2014). Most of the tree biomass models developed to estimate forest carbon have been fitted as species-specific models. However, tree allometry depends on several factors such as site conditions or species composition (*e.g.*, Barbeito *et al.*, 2014; Pretzsch, 2014). The applicability of species-specific biomass models developed in pure stands should be tested in mixed stands, and specific models for mixed stands or generalized equations for admixtures should also be developed in order to obtain accurate carbon estimations.

The belowground biomass stock is the least studied compartment due to the difficulty involved in sampling, measuring and estimating this stock. Nevertheless, the importance of this carbon compartment is unquestionable, particularly in Mediterranean areas where woody species are mainly resprouters. Root systems could account for more than 50% of total biomass in *Quercus* spp. coppices (*e.g.*, Canadell *et al.*, 1999; Serrada *et al.*, 2013; Cotillas *et al.*, 2016) with higher values in shrublands (e.g, Cañellas & San Miguel, 2000; Marziliano *et al.*, 2015). Belowground biomass in broadleaf stands was found to be 25% higher than in conifer stands (Montero *et al.*, 2005). High variability can be found depending on water and nutrient availability. Moreover, root loss in sampling procedures can account for up to 35% in the case of

Fagus sylvatica (Le Goff & Ottorini 2001), 15% in maritime pine (Danjon *et al.*, 2013) or 23% in some tropical forests (Niiyama *et al.*, 2010). It has been suggested that the degree of loss is dependent on tree size (the larger the tree, the greater the root biomass loss) and that losses are greater in stony soils and/or when the species shows a deeper rooting pattern (Danjon *et al.*, 2013). Accurate estimation is necessary in order to determine belowground biomass carbon stocks. Hence, more research is needed to identify a suitable sampling approach; comparing different methods to find the most accurate, cheapest and easiest method to perform this estimation on larger samples.

In the Mediterranean area, forest stands and soils have historically suffered profound, permanent alterations as a consequence of deforestation, cultivation, grazing, fires, etc., which are associated with degradation processes such as soil erosion and land use changes. These processes, together with the spatial and temporal variability of the Mediterranean climate have led to poor conditions for forest restoration and the evolution of soils may be unknown. Within the context of international agreements aimed at the reduction of CO_2 emissions (Kyoto Protocol, Paris Agreements, European Climate Policy), which refer to the role of afforestation in sequestering carbon, more studies focusing on soil carbon sequestration are needed to determine the response of the soil to afforestation, placing special emphasis on Mediterranean areas and on the way in which these processes take place in naturally regenerated areas of former agricultural land (Merino *et al.*, 2016).

Using forest management strategies to mitigate the effect of climate change, the timeframe for becoming a low-carbon economy may be lengthened. However, climate change influences the functioning of forests so management strategies should also aim to adapt forest ecosystems to change. The better forests are adapted to climate change the lower the impact will be. Thus, by furthering our understanding of forest drought adaptation, the effects of soil degradation and fertility loss or productivity reduction in the Mediterranean area due to global change, etc., it may be possible to develop suitable forest management strategies which combine both adaptation and mitigation (*e.g.*, Verchot *et al.*, 2007; D'Amato *et al.*, 2011; 2013; Sohn *et al.*, 2016).

Besides the trade-offs between adaptation and mitigation, in order to correctly address the abovementioned gaps in our knowledge as regards the impact of forest management on carbon sequestration, multidisciplinary studies must be undertaken which consider all the forest carbon components (biomass of trees and understory vegetation, soils, and off-site carbon storage), as well as the short and long-term effects of management. Therefore, a major challenge in the case of Mediterranean forests is to undertake new holistic experimental studies to compare forest management alternatives based on long-term monitoring.

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