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Evaluation of biomass, carbon storage capability, agroforestry interest of *Pinus pinea* L. and management practices to increase carbon stocks: a review

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SILVICULTURE

ABSTRACT

Background: Stone pine (*Pinus pinea* L.) is one of the characteristic species of the Mediterranean flora. This species has been used since ancient times because of its economic importance. This study was carried out because stone pine forests in the Mediterranean area, as carbon sinks, are one of the mitigation strategies considered to face climate change. Also, stone pine forests are of great socio-economic importance on an international scale due to the high demand for pine nuts and the important role of this emblematic species in agroforestry. The objectives of this study are, firstly, the evaluation of biomass and carbon storage capability and, secondly, the study of agroforestry interest of *Pinus pinea* L. and management practices to increase carbon stocks.

Results: A review of research and knowledge was carried out on the subject based on a selection of publications that have been made in the Mediterranean area. The main conclusions are that stone pine forests have a very high biomass stock and a high storage potential in the future. However, these forests could be a potential carbon reservoir in the coming years and thus on climate change mitigation. In addition, the practice of agroforestry in the stone pine ecosystem can create jobs and many sources of income for the local population and improve their living standards.

Conclusion: Finally, this review of research results can serve as an initial basis for refining management practices to improve the establishment of pine trees and tools to help forest managers in quantifying biomass, thereby contributing to the accurate estimation of carbon sequestration and stocks in stone pine stands and agroforestry practices.

Keywords: Stone pine; biomass; carbon stocks; agroforestry interest; management practices

HIGHLIGHTS

Forest management and quantification of stone pine biomass and carbon stocks.
Biomass accumulation under the stone pine and agroforestry interest of species.
Ground biomass estimation with very high spatial resolution satellite images.
Management practices used to increase biomass and carbon stocks.

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INTRODUCTION

Forest stands play a key role in CO_2 fixation. Carbon stored in forest ecosystems is distributed among three compositions: living tree biomass (stems, branches, foliage, roots), plant detritus (fallen branches and cones, forest litter, tree stumps, tree tops, logs) and soil. Plants acquire energy for their living structures through photosynthesis, which requires CO_2 captured by leaf stomata. Stand forests play an important role in mitigating global climate change. Forest ecosystems cover over 4.10^9 ha of the earth's surface (IPCC, 2007), with a quantified carbon (C) stock of 363 Pg C in living biomass (Pan et al., 2011). Forest biomass has become increasingly important in the global economy and in assessing stand development and monitoring (Gonçalves et al., 2019). Determination of forest biomass is very necessary for the assessment of forest stand dynamics and the monitoring of natural ecosystems under several environmental factors (Schroeder et al., 1997; Parresol, 1999). Biomass partitioning is a major factor in quantifying exploitable dendromass for timber yield or firewood (Tesfaye et al., 2015). Given the relationship between carbon stocks and the phytomass amount in forest ecosystems, in recent years, under the United Nations Framework Convention on Climate Change, and in particular the commitments contained in the Kyoto protocol, the need for accurate biomass accounting has arisen in most countries (Snowdon et al., 2000; Lehtonen et al., 2004; Somogyi et al., 2006; Vallet et al., 2006). In forest ecosystems of the Mediterranean area, wood production is considered a secondary function, whose quantification is very important to make the management strategy of forest stands as carbon sinks (Ruiz-Peinado et al., 2011). Quantifying the carbon balance in forests is one of the main challenges in forest management. Stand carbon stocks are usually quantified indirectly through biomass equations applied to forest inventories, frequently taking into account different stand biomass components (Ruiz-Peinado et al., 2011). Loewe and Delard (2017) have shown that stone pine is an important and key species for agroforestry and have used it for soil fixation and fertilization and livestock shading. Agroforestry systems play a crucial role in rural livelihoods by providing–employment, energy, nutritious food and a key range of other ecosystem goods and services (BBC, 2014). Eichhorn et al. (2006) found that the use of pine forest in these systems can expand the potential applications of agroforestry. Reisner et al. (2007) confirmed the potential of Pinus pinea in combined productive systems, with stone pine being recognized as key species for agroforestry systems (Fig. 1).

Stone pine is one of the nine most important dry fruit producing trees in the world (Loewe and Delard, 2016). Mutke et al. (2007) showed that ~~the~~ stone pine is also easily integrated into agroforestry systems due to its plasticity and beauty, and the important value of fruit in international markets. These authors confirmed that stone pine has been intercropped with agricultural crops in combined systems in Spain.

This work is a synthesis of tools to help forest managers quantify the biomass and carbon stocks of stone pine forest and the interest of this species in agroforestry.

Fig. 1 Stone pine stand in Tunisia.

CARBON SEQUESTRATION AND FOREST MANAGEMENT

Forest ecosystems play an irreplaceable role in regulating carbon (C) balance and maintaining global climate (Jassal et al., 2010). Forest degradation and other changes in land use have significantly affected the atmospheric carbon dioxide (CO_2) concentration (Okereke and Dooley, 2010). Carbon is stored in tree tissues in different amounts depending on factors such as species, growth rate, and leaf life span (Nowak et al., 2002; Gratani and Varone, 2007; Gratani et al., 2013). Plants with large crowns tend to sequestrate and store more C than trees with small crowns (Brack, 2002; Gratani and Varone, 2006) and changes of crown structure over time influence both the absolute stem growth and efficiency (Jack and Long, 1991). Carbon sequestration by forests is a major mechanism for mitigating global warming (Dixon et al., 1994; Lal, 2004) and has become a key issue for researchers and forest managers. Consequently, much of the current research in this area focuses on improving our quantification of carbon (C) stocks in the different components of forests, which are also of particular interest in terms of forest productivity (Lal, 2005). Reliable estimates of forest biomass are important for assessing forest stands and carbon stocks in accordance with the Kyoto Protocol on greenhouse gas reduction (Brown, 2002). Estimating forest stand biomass is generally considered a means of ensuring good ecosystem management and sustainability, and forest managers have applied different methods to obtain these estimates (Zianis and Mencuccini, 2004). Tree biomass plays an important role in sustainable stands management and in determining forest carbon stocks. Accurate estimates based on species-specific empirical data are necessary for regional and forestry survey and forest carbon management practices (Cutini et al., 2013). The production of greenhouse gases is the main concern of environmental researchers. This gas is the result of intensive human activities. There is a general consensus on the need to reduce this kind of gasses, and one of the main strategies is through CO_2 sequestration by forest biomass and soils. in this sense, carbon sequestration by means of forest management has become an extremely important tool (Hoen and Solberg, 1994; Brown et al., 1996; Canadell and Raupach, 2008). Carbon stored in forest ecosystems is of great importance from the point of view of forest management because, on the one hand, it is easily modified by silvicultural treatments (e.g., rotation length, thinning, etc.), and, on the other hand, it influences the average life span of forest products, especially wood. Del Río et al. (2017) find that in the Mediterranean area, forest ecosystems are characterized by an important role as a source of carbon and these forest stands offer ecosystem services of greater value than their direct production. Ruiz-Peinado et al. (2014) found that pine afforestation has proven to be a successful climate change mitigation strategy, as confirmed by the large amounts of carbon found in this reforestation in the middle of the rotation period. Results on the effects of thinning on carbon stocks showed a small loss in total biomass (including both on-site and off-site stock), but only when heavy thinnings were conducted.

Moreover, there was no effect on the forest soil (forest floor and mineral soil). Therefore, thinning treatments do not disrupt the potentially high rates of soil carbon sequestration rates associated with afforestation. Furthermore, the regular harvesting method avoids a decrease in forest floor carbon stock levels. Special consideration should be given to management strategies to increase carbon storage as forests may be considered a major global CO_2 sink that can confront the atmospheric CO_2 concentration increase (Power et al., 2012). Del Río et al. (2017) showed that pine stand management regimes in the Mediterranean zone influence on the evolution of carbon sequestration. Silvicultural interventions and forest stand age influenced carbon stocks.

BIOMASS AND CARBON STORAGE IN STONE PINE STANDS

In Mediterranean stone pine forests, Del Río et al. (2017) found that when annual biomass growth as well as annual cone production is considered, the uneven-aged stand product 0.14 Mg $C.ha^{-1}.yr^{-1}$ more carbon than the even-aged stand, which average a difference of 13.6 Mg $C.ha^{-1}$ over the 100 year period. In this sense Tab. 1 shows the annual increases in above-ground and below-ground biomass, annual cone production (dry weight) and their fixed C equivalents in even and uneven-aged stands of stone pine (Del Río M et al., 2017). From Tab. 1, we found that in the stand of stone pine, the biomass is 2322.5 $kg.ha^{-1}.yr^{-1}$ in even-aged stands and 2636.5 $kg.ha^{-1}.yr^{-1}$ in uneven-aged stands. In the same stand the amount of carbon fixed is 1.195 $Mg.C.ha^{-1}.yr^{-1}$ in even-aged stands and 1.334 $Mg.C.ha^{-1}.yr^{-1}$ in uneven-aged stands.

From Tab. 1 we conclude that uneven-aged stands of stone pine are more productive in biomass and carbon. Del Río et al. (2017) showed that in terms of productivity, the uneven-aged structure favors cone.

production, which is one of the main objectives in stone pine stand management practices. In terms of green cone weight (Fig.2), which is the commonly used trade unit, throughout the 100 year cycle uneven-aged stands produce 171 $kg.ha^{-1}.yr^{-1}$, while even aged stands only produce 120.8 $kg.ha^{-1}.yr^{-1}$. However, the contribution of cone production to CO_2 fixation can be considered negligible, as most cones are collected annually to obtain edible pine nuts, while the residuals of the industrial process of pine nut extraction are usually burned. In the study of allometric relationships for volume and biomass for stone pine in Italian coastal stands, Cutini et al. (2013) found that the wood basic density averaged 538 ± 11 $kg.m^3$. Carbon stocks in Spanish pine forests were above 249 million of Mg C in 2010, based on the second and third Spanish national forest inventories, the carbon stocks of *Pinus pinea* are 17.25 million of Mg C (Del Río et al., 2017). Regarding carbon sequestration in even and uneven-aged *Pinus pinea* stands, these authors concluded that the carbon sequestered in the even-aged stand reached a maximum of 84 $Mg.C.ha^{-1}$ at the end of the rotation period, while the simulated uneven-aged stand resulted in a maximum of 63 $Mg.C.ha^{-1}$ and a minimum of 30 $Mg.C.ha^{-1}$. Considering the total cumulative amount of carbon sequestered over the 100-year cycle, while even-aged stands accumulate 145 $Mg.C.ha^{-1}$, uneven-aged stands have sequestered 130 $Mg.C.ha^{-1}$, making them more efficient in this role. It should also be noted that the uneven-aged stand maintained a constant stock of sequestered carbon of over 27 $Mg.C.ha^{-1}$ that was never extracted from the forest. Cabanettes and Rapp (1978) found that the biomass production of *Pinus pinea* is 146 $t.ha^{-1}$, aboveground biomass is 124 $t.ha^{-1}$ and underground biomass is 22 $t.ha^{-1}$. In Tunisia, Ennajah et al. (2016) showed that aboveground biomass of the stone pine forest is 93 $t.ha^{-1}$ in the thinned stand and 113 $t.ha^{-1}$ in the unthinned stand. These authors concluded that thinned stand has a higher carbon stock compared to the control stand. The main role of silvicultural practices was to increase biomass production per unit of unit area (Whittaker et al., 1974) and carbon stock is directly correlated with stem volume. A study made by Moore et al. (2012), showed that silvicultural practices can lead to improved and maximized of carbon sequestration compared to the non silvicultural treatment, by controlling the density and stand growth.

Tab. 1 Categorization criteria for the condition of the cross-sections of the trunks of *Copaifera* sp.

	Structure	Aboveground	Belowground	cones	Total
Biomass ($kg{\cdot}ha^{-1}.yr^{-1}$)	Even-aged	1721.1	525.3	76.1	2322.5
	Uneven-aged	2034.4	520.9	108.2	2663.5
C fixation ($Mg.C.ha^{-1}.yr^{-1}$)	Even-aged	0.873	0.267	0.055	1.195
	Uneven-aged	1.031	0.265	0.038	1.334

Fig. 2 Stone pine cones.

Overall results highlight that stone pine structural traits and biomass change in response to tree age and silvicultural practices. The assessment of forest carbon stocks is based on estimates of forest biomass, usually by applying biomass equations to forest inventories (Faias et al., 2018). These authors found that studies regarding forest biomass in stone pine species (Tab. 2) have been carried out in the Mediterranean basin, namely Italy (Cutini et al., 2013), Spain (Montero et al., 2005; Ruiz-Peinado et al., 2011) and Portugal (Correia et al., 2010). Correia et al. (2010) indicated that aboveground biomass allometry in *Pinus pinea* is not comparable to other pines and varies considerably with stands characteristics. These authors found that biomass expansion factors of aboveground decreased between open (1.33 ± 0.03 $Mg.m^{-3}$) and closed stands (1.07 ± 0.01 $Mg.m^{-3}$) due to a change in the biomass allocation pattern from stem to branches. The means wood basic density was 0.50 ± 0.01 $Mg.m^{-3}$, but it varied with tree dimensions and the root/branch ratio found was 0.30 ± 0.03. A carbon sequestration simulation made by Del Rio et al. (2008) using an integrated single tree model (PINEA2) in even and uneven aged *P. pinea* stands over a 100-year period, estimated 1.2 to 1.5 Mg of carbon sequestered per ha and per year ($Mg.C.ha^{-1}.yr^{-1}$). Correia et al. (2010) found that the aboveground estimates were within the range of values reported in the literature for other pines. The total biomass of stone pine (aerial and root) for the Alentejo region is 47.6 $t.ha^{-1}$ with pure stands and 5.1 $t.ha^{-1}$ for plantations (IFN5, 2010). In the study of *Pinus pinea* aboveground biomass estimation with very high spatial resolution satellite images, Gonçalves et al. (2017a) found that the fitted functions of aboveground biomass per plot (Wps) against tree crown horizontal projection (CHPps) and cumulative aboveground biomass per plot (Wpsc) against Tree crown horizontal projection (CHPpsc) have statistical properties that indicate their good performance, these authors found the equations illustrated in Tab. 3. Site-specific biomass equations and expansion factors for stone pine have already been developed from harvested trees collected in Italy by Cutini et al. (2013), in Spain by Montero et al. (2005), Ruiz-Peinado et al. (2011) and Portugal by Correia et al. (2010) showed in Tab. 4.

Tab. 2 Aboveground biomass model of stone pine (Faias et al., 2018).

	Country	Aboveground biomass model	References
General Model	Spain	0.11694 d2.424	Montero et al. (2005)
	Italy	0.054 d2.594	Cutini et al. 2013
	Portugal	280.1 C2.22h0.19	Correira et al. 2010

D : diameter at breast height (cm) ; C ; h : tree height (m) ; C : circumference at breast height (cm).

Tab. 3 Allometric function of aboveground biomass of stone pine estimated with very high spatial resolution satellite images (Gonçalves et al., 2017a).

Allometric function	R^2	R_{2aj}
Wps = 12.4076 x CHPps	0.893	0.890
Wpscs = 14.1471 x CHPps	0.995	0.995

Wps : above ground biomass per plot ; CHPps : Tree crown horizontal projection ; W psc : cumulative above ground biomass per plot

Tab. 4 Pulished site-specific systems of biomass equations, fitting dataset d range (cm) and correspondent evaluation statistics. Abbreviations stand for : d, tree diameter at breast height (cm); c, circumference at breast height (cm); h, tree height (m) (Correia et al., 2018).

Allometric function	Biomass component	Model	Published statistics
Italy D range : [10-50] Cutini et al. (2013)	Stem	0.091 d2.346	RMSE = 70.85
	Needles	0.009 d2.537	RMSE by local 3.91;16.39 ; 2.74; 4.93
	Woody	0.045 d2.602	RMSE = 85.14
	Aboveground	∑ components	
Portugal D range : [7-56] Correira et al. (2010)	Wood	18.85 c1.68 h0.95	R^2_{aj} = 0.93
	Bark	8.08 c1.55 h0.47	R^2_{aj} = 0.82
	Needles	22.27 c1.76 (h/d) (-0.5)	R^2_{aj} = 0.63
	Branches	184.94 c3.03	R^2_{aj} = 0.74
	Aboveground	∑ components	
Spain D range : [9-63] Ruiz-Peinado et al. (2011)	Stem	0.0224 d1.923h1.0193	R^2_{aj} = 0.99 RMSE = 36.76
	Needles with thin branches (< 2 cm)	21.927-2.827h+ 0.0707 d2	R^2_{aj} = 0.90 RMSE = 19.65
	Medium branches (2-7 cm)	0.0525 d^2	R^2_{aj} = 0.80 RMSE = 29.46
	Thick branches	[0.247 (d-22.5)2]Z If d ≤ 22.5 cm then Z = 0 If d > 22.5 cm then Z = 1	R^2_{aj} = 0.86 RMSE = 46.17
	Aboveground	∑ components	
	Roots	0.117 d^2	R^2_{aj} = 0.98 RMSE = 14.86

With the aim of developing a system of biomass equations for aboveground and belowground biomass for the Mediterranean Stone pine (three Mediterranean countries: Italy, Portugal and Spain) Correia et al. (2018) found that the new biomass equations found in their study (Tab. 5) improved the accuracy of biomass estimates, particularly for the aboveground components of higher dimension trees and for the root component, being highly suitable for use in regional and national biomass forest calculations. This is, to date, the most exhaustive database on harvested stone pine stands in the world. The newly developed equations performed better than regional equations and are suitable for quantifying biomass at local or national level. Correia et al. (2018) developed a new Mediterranean system of biomass equations, wich allows for more accurate estimation of aboveground biomass of stone pine across a wide range of diameter classes and across different sites. The study also included a new and more precise belowground biomass model by sharing existing data (Tab. 5). In comparison with *Pinus pinaster*, Ruiz-Peinado et al. (2013) found that the total carbon stocks present in unthinned plots of *Pinus pinaster* were 317 $Mg.ha^{-1}$; in the moderately thinned plots they were 256 $Mg.ha^{-1}$ and in the case of heavily thinned plots, 234 $Mg.ha^{-1}$. These authors found that these differences were mainly due to the carbon stock in the living biomass, which decreased with the intensity

Tab. 5 Formulation of the Mediterranean system of biomass equations for the aboveground biomass, whère MT-d includes only tree d (cm), MT-dh includes tree d and h (m) and RMSE is in kg. For each parameter, the significance (p-value) is presented. (Correia et al., 2018).

Allometric function	Biomass component	Model	k	α	β	R^2_{aj}	RMSE
MT-d	Stem	kd^{α}	0.002423 (<0.0001)	3.246929 (<0.0001)		0.931	98.2
	Branches	kd^{α}	0.618358 (<0.0001)	1.678759 (<0.0001)		0.797	76.7
	Needles	$k\,(d/100)^{\alpha}$	2061.774 (<0.0001)	4.248054 (<0.0001)		0.776	33.0
	Aboveground	∑ components				0.961	115.7
MT-dh	Stem	$K\,d^{\alpha}\,(h/d)^{\beta}$	0.008797 (<0.0001)	2.871281 (<0.0001)	-0.19326 (<0.0001)	0.930	98.9
	Branches	$K\,d^{\alpha}\,h^{\beta}$	0.060502 (<0.0001)	1.897782 (<0.0001)	0.527179 (<0.0001)	0.852	65.5
	Needles	$K\,(d/100)^{\alpha}\,(h/d)^{\beta}$	49.37346 (<0.0001)	2.528243 (<0.0001)	-2.01953 (<0.0001)	0.888	23.4
	Aboveground	∑ components				0.960	116.9

of thinning. However, soil carbon stocks, forest soil and mineral soil, were not influenced by silvicultural practices, especially thinning, with all stands showing very similar values 102–107 Mg.C.ha^{-1} for total soil; 15–19 Mg.C.ha^{-1} for forest soil; 87–88 Mg.C.ha^{-1} for mineral soil). Ruiz-Peinado et al. (2013) reported that total carbon between managed and unmanaged *Pinus pinea* stands highlight the importance of forest management on mitigation effects. In this sense, in situ carbon stocks are therefore not the only relevant indicators for carbon sequestration, as harvested biomass can contribute effectively to carbon sequestration in managed forests.

BIOMASS AND CARBON STORAGE SHRUB UNDER STONE PINE FOREST

Although tree biomass represents the main carbon sink in forests ecosystems (Beedlow et al., 2004), in some area's shrub biomass could be as important as tree biomass in terms of carbon sequestration (Pasalodos-Tato et al., 2015). These authors found that the importance of shrub formations in the Mediterranean area both in terms of the area occupied and the carbon sequestered by them is currently recognized. In the study of shrub biomass accumulation under *Pinus pinea* , Pasalodos-Tato et al. (2015) inventoried using destructive sampling an annual growth rate of 16.73 Mg.ha^{-1} and 1.14 Mg.ha^{-1}.yr^{-1}, respectively. Heather and big-size Cistaceae formations had the highest values of biomass accumulation (24.99 and 21.01 Mg.ha^{-1}, respectively), while the highest values of annual growth rate were achieved by leguminous gorse shrubs and, again, big-size Cistaceae shrubs (1.49 and 1.64 Mg.ha^{-1}.yr^{-1}, respectively). In the carbon sequestration of Mediterranean shrubs, Gratani et al. (2014) noted that biomass was the largest in 104-year-old tree stands (241.1 ± 9.8 t.ha^{-1}) and carbon stored (Cst) varied from 0.01 ± 0.005 to 1.63 ± 0.07 Mg.ha^{-1} (15 and 104 year-old trees, respectively). Merino et al. (1990) obtained a biomass value of 4.9 Mg.ha^{-1} for cistus and 21.9 Mg.ha^{-1} for heathers in South-East of Andalusia was much lower than that obtained by Pasalodos-Tato et al. (2015) which is in the order of 6.26 and 21.01 Mg.ha^{-1} formation of cistus respectively. The results of a study by Marquez et al. (1989) on cistus formations in the neighboring province of Badajoz (Spain), indicate amounts

ranging from 5.0 to 37.7 Mg.ha^{-1} according to age, with an average value of 23.2 Mg.ha^{-1}. There is rather less agreement with the results obtained by Fernandez et al. (1995), who presented biomass estimates for the northwestern part of the region for cistus and mixed shrubs ranging from 8.1 to 15.2 Mg.ha^{-1} and from 41.1 to 66.8 Mg.ha^{-1} respectively. Basanta (1982) reported values of 28.9 Mg.ha^{-1} for shrub (without specified dominant species) in the mountainous area of the Andalusian region. These results differ from those obtained as the average amount of biomass found in Andalusia (without differentiating between formations) was 16.7 Mg.ha^{-1}. Under stone pine forests, Adili et al. (2013) found that biomass of understorey vegetation (woody species, graminoids and forbs) was positively correlated with light transmittance (Tab. 6). The lower transmittance class (6.2–11.5%) showed lower understorey biomass, with 223 kg.ha^{-1} for woody species, 4.9 kg.ha^{-1} for graminoids and 1.6 kg.ha^{-1} for forbs. Understorey biomass was significantly greater in the higher transmittance class (19.8–30.6%) (17112 kg.ha^{-1} for woody vegetation, 167 kg.ha^{-1} for graminoids and 152 kg·ha^{-1} for forbs). Litter quantity increases with canopy cover and decreases with increasing light availability. Consequently, litter biomass was linked to light transmittance (Adili et al., 2013). Finally, shrub biomass under pine forest and growth rate are very relevant for forest management in Mediterranean regions, not only for quantifying carbon sequestration capacity, but also for the development of guidelines for fire prevention as well as for assessing the role of forest ecosystems as wildlife habitats (Pasalodos-Tato et al., 2015).

Tab. 6 Understorey biomass (kg·ha^{-1}) of understorey woody species, graminoids, forbs and litter relative to transmittance in three coastal *Pinus pinea* forest located in north Tunisia (Adili et al., 2013).

Transmittance class	6.2-11.5	11.6-14.8	14.9-19.7	19.8-30.6
Woody species	223	1188	3371	17112
Graminoids	4.95	9.2	34.6	166.8
Forbs	1.6	5.2	49.8	151.5
Litter	11440	7426	4390	2909

AGROFORESTRY INTEREST OF STONE PINE

Agroforestry systems are recognized for their importance in biomass production, both for carbon stocks (in vegetation and soil) and as a source of biomass for energy production (Jose and Bardhan, 2012). These systems improve the sustainability and durability of production (Nerlich et al., 2013; Eichhorn et al., 2006; Jose et al., 2004). Mutke et al. (2012) showed that stone pine has potential as a crop in agroforestry systems; in tree lines, such as shelterbelts adjacent to farmland or pastures; or in low-density orchard plantations. These authors found that most reforestation for pine nut production is still managed as extensive forest or agroforestry systems, and trees are mostly grown from seeds. Bono and Aletà (2013) showed that grafted plantations for cone production could be an important alternative on low quality agricultural lands. These plantations have various advantages over traditional forest harvesting: early bearing, possibility of using more productive genotypes and more adapted rootstocks to the soil, easy harvesting, better control against cone pillage. These authors concluded that the cone yield was registered, with 840 kg. ha^{-1}. Loewe and Delard (2019) tested agroforestry systems including stone pine and agricultural crops (forage oat and potatoes) and sheep grazing for sheep production. These authors found that forage production in these plots was not enough to support permanent grazing; however, sheep grazing in regulated periods contributes to sheep production. Gonçalves et al. (2017b) showed that most stone pine (*Pinus pinea* L.) stands are managed as agroforestry systems, whose main production is fruit, due to the edible and highly nutritious kernels, and are frequently associated to natural or seeded pastures and grazing. These authors found that the stands are characteristic of agroforestry systems, whose main production is fruit associated with natural or seeded pasture and grazing. The result of Loewe and Delard (2019) indicates the overall beneficial effects of the system on the tree reproductive development, and could be an advantage for traditional plantations with seedlings, which are significantly less expensive than grafted plants. Agrimi and Ciancio (1994) confirmed the possibility to combine stone pine and animals. Loewe and Delard (2019) found that grazing reduces weed and shrub growth, fire risk, and the cost of periodic mechanical cleaning. These authors concluded that net present value was almost seven times higher in the agroforestry system than in pure stone pine reforestation; therefore, this system can contribute to the local and national economy. Soil fragmentation and nutrient enrichment through animal defecation during grazing has been reported, accelerating litter decomposition and nitrogen incorporation, and reducing pine needle accumulation and fire risk (Mancilla-Leyton et al., 2013). Loewe and Delard (2019) suggest that it is possible to associate stone pine cultivation with intercropped annual cultures and also with controlled grazing, with important tree development values, as it has been demonstrated for other fruit forest species (Chifflot et al., 2005). Gonçalves et al. (2017b) found that the management of stone pine stands seems to be better suited to agroforestry systems with free-growing trees, especially if they have a uniform spatial distribution and neighbors have similar sizes, as this limits competition and enhances fruit production in the outer crowns. In addition, Gonçalves et al (2017b) showed that low crown cover favors grazing and pasturing, allowing product diversification, and that trees and vegetation cover in pastures reduce erosion potential, which is particularly important in the Mediterranean area where precipitation is variable over time. Loewe and Delard (2019) showed that, from an economic point of view, we found the combined system to be significantly more profitable than stone pine monoculture oriented to cone and nut production. Economic results can improve if the owner adds primary elaboration to sell in-shell pine nuts. These authors found that the species suitable for its establishment in combined agroforestry systems based on trees for both nuts and wood, intercropped with agricultural crops and animal grazing. The high prices obtained for this nut in international markets have made it an attractive opportunity as an alternative crop on rain-fed farmland or in agroforestry systems (Mutke et al., 2012). Loewe and Delard (2019) found that the stone pine-agricultural crops-sheep grazing system showed a positive economic impact; given the socio-economic limitations characteristic of this sector. These results serve to encourage the authorities to provide subsidies for the government establishment and proper management of agroforestry systems in order to improve the rural economy and living standards of the local population.

MANAGEMENT PRACTICES REDUCE EMISSIONS AND/OR INCREASE CARBON STOCKS

The forest management practice options available to minimize emissions and/or maximize carbon stocks can be presented in four recommendations according to Nabuurs et al. (2007):

1. Protect forests, maximize reforestation of degraded and unused areas, and limit clearing and other forest ecosystem degradation activities;
2. Apply appropriate silvicultural treatments and good forest stand management (thinning, pruning, maintenance, species mixing, etc.);
3. Maintain or increase ecosystem carbon density by protecting forest stands based on the application of appropriate management plans, fire and pest and disease control in forests;
4. Maximize off-site carbon stocks in wood products and promote forest products as substitutes for fuels and other materials (e.g., biomass, building materials, etc.)

CONCLUSION

In conclusion of this literature review, we found that the determination of the biomass and carbon balance of stone pine forests in the Mediterranean area is important and useful for the management of forest ecosystems. Quantifying the carbon balance of forests is one of the main challenges in current forest management. The management practices discussed in this synthesis allow reducing gas emissions and increasing carbon stocks. Agroforestry systems are recognized for their importance in biomass production, both for carbon sequestration (in vegetation and soil) and as a source of biomass for energy. This synthesis could justify government investment in the establishment and management of forest ecosystems to improve the rural economy.

COMPETING INTERESTS

Authors declare that there are no competing interests.

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REFERENCES

ADILI, B.; EL AOUNI, M.H.; BALANDIER, P. Influence of stand and tree attributes and silviculture on cone and seed productions in forests of *Pinus pinea* L., in northern Tunisia. Options Méditerranéennes, v.105, p.9-14, 2013.

AGRIMI, M.; CIANCIO, O. Italian Stone pine (Il pino domestico) (*Pinus pinea* L.). FAO Silva Mediterranea, Larnaca. 1994.

BASANTA, A. Matorral serial en Sierra Morena, Estudio ecologico de las respuestas del matorral a distintas intervenciones humanas en el coto Nacional "La pata del caballo". Tesis Doctoral, Universidad de Sevilla, Huelva. 1982

BBC. Eva Mueller : UN urge action on forest diversity. http://m.bbc.com/news/science-environment-27963330. 2014.

BEEDLOW, P.A.; TINGEY, D.T.; PHILLIPS, D.L.; HOGSETT, W.E.; OLSZYK, D.M. Rising atmospheric CO_2 and carbon sequestration in forests. Frontiers in Ecology and the Environment, v.2, p.315–332. 2004.

BONA, D.; ALETA, N. Cone yield evaluation of a grafted *Pinus pinea* L. trial. Mediterranean Stone Pine for Agroforestry. Options Méditerranéennes, v.105, p.34-41, 2013.

BRACK, C.L. Pollution mitigation and carbon sequestration by an urban forest. Environmental Pollution, v.116, p.195–200, 2002.

BROWN, S. Measuring carbon in forests: current status and future challenges. Environmental Pollution, v.16, p.363–372, 2002.

BROWN, S.; SATHAYE, J.; CANNELL, M.; KAUPPI, P.E. Mitigation of carbon emissions to the atmosphere by forest management. The Commonwealth Forestry Review, V.75(1), p.80–91, 1996.

CANADELL JG.; RAUPACH, M.R. Managing forests for climate change mitigation. Science, v.320 (5882), p.1456–1457, 2008.

CHIFFLOT, V.; BERTONI, G.; CABANETTES, A.; GAVALAND, A. Beneficial effects of intercropping on the growth and Nitrogen status of young wild cherry and hybrid walnut trees. Agroforestry Systems, v.66(1), p.13–26, 2005.

CORREIA, A.C.; TOME, M.; PACHECHO, C.A.; FAIAS, S.; DIAS, A.C.; FREIRE, J.; CARVALHO, P.O.; PEREIRA, J.S. Biomass allometry and carbon factors for a Mediterranean pine (*Pinus pinea* L.) in Portugal. Agroforestry Systems, v19, p. 418-433, 2010.

CORREIA, AC.; FAIAS, S.P.; RUIZ-PEINADO, R.; CHIANUCCI, F.; CUTINI, A.; FONTES, L.; MANETTI, M.C.; MONTERO, G.; SOARES, P.; TOME, M. Forest Ecology And Management, v.429, p.425–436, 2018.

CUTINI, A.; CHIANUCCI, F.; MANETTI, M.C. Allometric relationships for volume and biomass for stone pine (*Pinus pinea* L.) in Italian coastal stands. iForest (early view): e1-e7, 2013.

DEL RIO, M.; BARBEITO, I.; BRAVO-OVIEDO, A.; CALAMA, R, CAÑELLAS, I.; HERRERO, C.; BRAVO, F. Carbon sequestration in Mediterranean pine forests. In: Managing Forest ecosystems: the chalenge of climate change (Bravo F., Lemay V., Jandl R., Gadow K.V., eds). Netherlands, Kluwer Academic Publishers, v.17, p.15-241, 2008.

DEL RIO, M.; BARBEITO, I.; BRAVO-OVIEDO, A.; CALAMA, R.; CAÑELLAS, I.; HERRERO, C.; MONTERO, G.; MORENO-FERNANDEZ, D.; RUIZ-PEINADO, R.; BRAVO, F. Mediterranean Pine Forests: Management Effects on Carbon Stocks. Managing Forest Ecosystems: The Challenge of Climate Change, Managing Forest Ecosystems, book series, MAFE, v.34, 2017.

DIXON, R.K.; BROWN, S.; HOUGHTON, R.A.; SOLOMON, A.M.; TREXLER, M.C.; WISNIEWSKI, J. Carbon pools and flux of global forest ecosystem. Science, v.263, p.185–190, 1994.

EICHHORN, M.P.; PARIS P.; HERZOG, F.; INCOLL, L.D.; LIAGRE, F.; MANTZANAS, K.; MAYUS, M.; MORENO, G.; PAPANASTASIS, V.P.; PILBEAM, D.J.; PISANELLI, A.; DUPRAZ, C. Silvoarable systems in Europe: past, present and future prospects. Agroforestry Systems, v.67, p.29–50, 2006.

ENNAJAH, A.; KACHOUT-SAI, S.; KHALDI, A.; ELAOUI, M.; LAAMOURI, A.; FEZZANI, T.; CHERNI, T.; ELEUCH, S.; NASR, Z. Interactive Effects of Ecosystem Managements on Gas Exchange, Water Use Efficiency and Carbon Stock in *Pinus pinea* Forests. Journal of Chemical, Biological and Physical Sciences, v.6(3), p.1044-1059, 2016.

FAIAS D, CORREIA A., FONTES L, SOARES P, TOME M, RUIZ-PEINADO R. MONTERO G, CHIANUCCI F, CUTINI A, MANETTI M. Stone pine biomass allometric equations analysis for the Mediterranean area. Project AGRO 8.1 (nº 543) – Carbon sequestration and sustainable forest management in Portugal and by the *Pinea* project: PTDC/AGR-FOR/3804/2012. 2018.

FERNANDEZ, R.; RODRIGUEZ, M.; MARTIN, A.; GARCIA, J.L.; INFANTE, J.M.; LEIVA, M.J.; RODRIGUEZ, J.J.; GALLARDO, A. Mediterranean oak forests: basis for appropriate protection strategy, Final Report EV5 V-CT92-0210, CEC, unpub, 1995. p.165.

GONÇALVES, A.C.; AFONSO, A.; PEREIRA, D.G.; PINHEIRO, A. Influence of umbrella pine (*Pinus pinea* L.) stand type and tree characteristics on cone production. Agroforestry Systems, v.91(6), p.1019–1030, 2017b.

GONÇALVES, A.C.; SOUSA, A.M.O. Silva JRM. *Pinus pinea* above ground biomass estimation with very high spatial resolution satellite images. In: Carrasquinho I. (ed.), Correia A.C. (ed.), Mu tke S. (ed.). Mediterranean pine nuts from forests and plantations. Zaragoza: CIHEAM. Série A: Options Méditerranéennes, v.122, p.49-54, 2017a.

GONÇALVES, A.C.; SOUSA, A.M.O.; MESQUITA, P. Functions for aboveground biomass estimation derived from satellite images data in Mediterranean agroforestry systems. Agroforestry Systems, v.93, p.1485–1500, 2019.

GRATANI, L.; VARONE, L. Carbon sequestration by *Quercus ilex* L. and *Quercus pubescens* Willd. and their contribution to decreasing air temperature in Rome. Urban Ecosystems, v.9, p.27–37, 2006.

GRATANI, L.; VARONE, L. Plant crown traits and carbon sequestration capability by Platanus hybrida Brot. in Rome. Landscape and Urban Planning, v.81, p.282–286, 2007.

GRATANI, L.; VARONE, L.; RICOTTA, C.; CATONI, R. Mediterranean shrublands carbon sequestration: environmental and economic benefits. Mitigation and Adaptation Strategies for Global Change, v.18, p.1167–1182, 2013.

HOEN, H.F.; SOLBERG, B. Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. Forest Science, v.40, n.3, p.429–451, 1994.

IFN5. Inventario Florestal Nacional. IFN5-2006, Portugal Continental. Lisbon: Autoridale Florestal Nacional. (In portugueuse). 2010.

IPCC. Climate change: mitigation of climate change. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge. 2007.

JACK, S.B.; LONG, J.N. Structure, production and leaf area dynamics: a comparison of lodgepole pine and sunflower. Annals of Botany, v.68, p.247–252, 1991.

JASSAL, R.S.; BLACK, T.A.; CAI, T.B.; ETHIER, G.; PEPIN, S.; BRUMMER, C.; NESIC, Z.; SPITTLEHOUSE, D.L.; TROFYMOW, J.A. Impact of nitrogen fertilization on carbon and water balances in a chronosequence of three Douglas-fir stands in the Pacific Northwest. Agricultural and Forest Meteorology, v.150, p.208–218, 2010.

JOSE, S.; BARDHAN, S. Agroforestry for biomass production and carbon sequestration: an overview. Agroforetry Systems, v.86, p.105–111, 2012.

JOSE, S.; GILLESPIE, A.R.; PALLARDY, S.G. Interspecific interac-tions in temperate agroforestry. Agroforestry Systems, v.61, p.237–255, 2004.

LAL, R. Forest soils and carbon sequestration. Forest Ecology and Management, v.220. p.242–258, 2005.

LAL, R. Soil carbon sequestration to mitigate climate change. Geoderma. v. 123, p.1–22, 2004.

LEHTONEN, A.; MAKIPAA, R.; HEYKKINEN, J.; SIEVANEN, R.; LISKI, J. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management, v.188, p.211–224, 2004.

LOEWE, M.V.; DELARD, RC. Produccion de pinon mediterraneo (*Pinus pinea* L.). Manual N: 48. INFOR (in Spanish). 2016.

LOEWE, V.; DELARD, C. Stone pine (*Pinus pinea* L.): an interesting species for agroforestry in Chile. Agroforestry Systems, v.93, p.703–713, 2019.

MANCILLA-LEYTON, J.M.; SANCHEZ-LINEROS, V.; VICENTE, A.M. Influence of grazing on the decomposition of *Pinus pinea* L. needles in a silvopastoral system in Donana, Spain. Plant Soil, v.373, p.173–181, 2013.

MARQUEZ, M. ; NUNEZ, E. ; ESCUDERO, J.C. Dinamica del nitrogeno en un gradiente de edad de Cistus ladanifer L. Options Méditerranéennes, v.3, p.151–155, 1989.

MERINO, O.; MARTIN, M.P.; MARTIN, A.; MERINO, J. Successional and temporal changes in primary productivity in two Mediterranean scrub ecosystems. Acta Oecologica, v.11(1), p.103–112, 1990.

MONTERO, G. ; RUIZ-PEINADO, R. ; MUÑOZ, M. Producción de biomasa y fijación de CO_2 por los bosques españoles. Monografías INIA, Serie Forestal no. 13, Madrid, Spain, pp. 270. 2005.

MOORE, T.Y.; RUEL, J.C.; LAPOINTE, M.A.; LUSSIER, J.M. Evaluating the profitability of selection cuts in irregular boreal forests: an approach based on Monte Carlo simulations. Forestry, v.85, p.63-77, 2012.

MUTKE, S.; CALAMA, R.; GONZALEZ-MARTINEZ, S.C.; MONTERO, G.; GORDO, J.; BONO, D.; GIL, L. Mediterranean Stone Pine: botany and horticulture. Horticultural Reviews, v.39, p.153–201, 2012.

MUTKE, S.; CALAMA, R.; GORDO, J.; GIL, L. El uso del pino pinonero como especie de frutal en sistemas agroforestales de secano. Cuadernos de la Sociedad Espanola de Ciencias Forestales, v.22, p.137–142, 2007.

NABUURS, G.J. ; MASERA, O. ; ANDRASKO, K. ; BENITEZ-PONCE, P. ; BOER, R.; DUTSCKHE, M.; ELSIDDIG, E.; FORD ROBERTSON, J.; FRUMHOFF, P.; KARJALAINEN, T.; KRANKINA, O.; KURZ, W.A.; NATSUMOTO, M.; OYHANTCABAL, W.; RAVINDRANATH, N.H.; SANZ SANCHEZ, M.J.; ZHANG, X. Forestry. In: Metz B, Davidson OR, P.R. B, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. 2007.

NERLICH, K.; GRAEFF-HONNINGER, S.; CLAUPEIN, W. Agro-forestry in Europe: a review of the disappearance of traditional systems and development of modern agroforestry practices, with emphasis on experiences in Germany. Agroforestry Systems, v.87. p.475–492, 2013.

NOWAK, D.J.; STEVENS, J.C.; SISINNI, S.M.; LULEY, C.J. Effects of urban tree management and species selection on atmospheric carbon dioxide. Journal of Arboriculture, v.28, p.113–122, 2002.

NUNES, L.; PATRICIO, M.S.; TOME, J.; TOME, M. Carbon and nutrients stocks in even-aged maritime pine stands from Portugal. Forest Systems, v.19, p.434–448, 2010.

OKEREKE, C.; DOOLEY, K. Principles of justice in proposals and policy approaches to avoided deforestation: towards a postKyoto climate agreement. Global Environments Change, v.20, p.82–95, 2010.

PAN, Y.; BIRDSEY, R.A.; FANG, J.; HOUGHTON, R.; KAUPPI, P.E.; KURZ, W.A.; PHILLIPS, O.L.; SHVIDENKO, A.; LEWIS, S.L.; CANADELL, J.G.; CIAIS, P.; JACKSON, R.B.; PACALA, S.W.; MCGUIRE, A.D.; PIAO, S.; RAUTIAINEN, A.; SITCH, S.; HAYES, D. A large and persistent carbon sink in the world's forests. Science, v.333, p.988–993, 2011.

PARRESOL, B.R. Assessing tree and stand biomass: a review with examples and critical comparisons. Forest Sciences, v.45(4), p.573–593, 1999.

PASALODOS-TATO, M.; RUIZ-PEINADO, R.; DEL RIO, M.; MONTERO, G. Shrub biomass accumulation and growth rate models to quantify carbon stocks and fluxes for the Mediterranean region. European Journal of Forest Research, v.134, p.537–553, 2015.

POWER, M.J.; MAYLE, F.E.; BARTLEIN, P.J.; MARLON, J.R.; ANDERSON, R.S.; BEHLING, H.; BROWN, K.J.; CARCAILLET, C.; COLOMBAROLI, D.; GAVIN, D.G.; HALLETT, D.J.; HORN, S.P.; KENNEDY, L.M.; LANE, C.S.; LONG, C.J.; MORENO, P.I, PAITRE, C.; ROBINSON, G.; TAYLOR, Z.; WALSH, M.K. Climatic control of the biomass-urning decline in the Americas after ad 1500. Holocene, Power, M., Mayle, F., Bartlein, P., Marlon, J., Anderson, R., Behling, H., … Walsh, M. Climatic control of the biomass-burning decline in the Americas after ad 1500. The Holocene, v.23(1), p.3–13. 2012.

REISNER, Y.; DE FILIPPI, R.; HERZOG, F.; PALMA, J. TARGET REGIONS FOR SILVOARABLE AGROFORESTRY IN EUROPE. Ecological Engineering, v.29, p.401–418, 2007.

RUIZ-PEINADO, R.; BRAVO-OVIEDO, A.; LOPEZ-SENESPLEDA, E.; MONTERO G RIO, M. Do thinnings influence biomass and soil carbon stocks in Mediterranean maritime pine woods? European Journal of Forest Research, v.32, p.253–262, 2013.

RUIZ-PEINADO, R.; BRAVO-OVIEDO, A.; MONTERO, G.; DEL RIO, M. Carbon stocks in a Scots pine afforestation under different thinning intensities management. Mitigation and Adaptation Strategies for Global Change, 2014.

RUIZ-PEINADO, R.; DEL RIO, M.; MONTERO, G. New models for estimating the carbon sink capacity of Spanish softwood species. Forest Systems, v.20, p.176-188, 2011.

SCHROEDER, P.; BROWN, S.; MO, J.; BIRDSEY, R.; CIESZEWSKI, C. Biomass estimation for temperate broadleaf forests of the United States using inventory data. Forest Sciences, v.43(3), p.424–434, 1997.

SNOWDON, P.; RAISON, J.; KEITH, H.; RITSON, P.; GRIERSON, P.; ADAMS, M.; MONTAGU, K.; BI, H.; BURROWS, W.; EAMUS, D. Protocol for sampling tree and stands biomass. National Carbon Accounting System, Technical Report No. 31, Australian Greenhouse Office, Canberra. 2002.

SOMOGYI, Z.; CIENCIALA, E.; MAKIPAA, R.; MUUKKONEN, P.; LEHTONEN, A.; WEISS P. Indirect methods of large-scale forest biomass estimation. European Journal of Forest Research, V.126(2), p.197–207, 2006.

TESFAYE, MA.; BRAVO-OVIEDO, A.; BRAVO, F.; RUIZ-PEINADO, R. 2015. Aboveground biomass equations for sustainable production of fuelwood in a native dry tropical afro-montane forest of Ethiopia. Annals of Forest Science. 2015.

VALLET, P.; DHOTE, J.F.; LE MOGUEDEC, G.; RAVART, M.; PIGNARD, G. Development of total aboveground volume equations for seven important forest tree species in France. Forest Ecology and Management; v.229, p.98–110, 2006.

WHITTAKER, R.H.; BORMANN, F.H.; LIKENS, G.E.; SICCANA T.G.; BROOD, H. Ecosystems study: forest biomass and production. Ecological Monographs, v.44, p.233-254, 1974.

ZIANIS, D.; MENCUCCINI, M. On simplifying allometric analyses of forest biomass. Forest Ecology and Management, v.187, n.2-3, p.311-332, 2004.