

Do thinnings influence biomass and soil carbon stocks in Mediterranean maritime pinewoods?

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Abstract The effects of silvicultural treatments on carbon sequestration are poorly understood, particularly in areas like the Mediterranean where soil fertility is low and climatic conditions can be harsh. In order to improve our understanding of these effects, a long-term thinning experiment in a stand of Mediterranean maritime pine (*Pinus pinaster* Ait.) was studied to identify the effects of thinning on soil carbon (forest floor and mineral soil), above and belowground biomass and fine and coarse woody debris. The study site was a 59-year-old pinewood, where three thinnings of differing intensities were applied: unthinned (control), moderate thinning and heavy thinning. The three thinning interventions (for the managed plots) involved whole-tree harvesting. The results revealed no differences between the different thinning treatments as regards the total soil carbon pool (forest floor + mineral soil). However, differences were detected in the case of living aboveground biomass and total dead wood debris between unthinned and thinned plots; the former containing larger amounts of carbon. The total carbon present in the

unthinned plots was 317 Mg ha⁻¹; in the moderately thinned plots, it was 256 Mg ha⁻¹ and in the case of heavily thinned plots, 234 Mg ha⁻¹. Quantification of these carbon compartments can be used as an indicator of total carbon stocks under different forest management regimes and thus identify the most appropriate to mitigate the effects of global change. Our results indicated that thinning do not alter the total soil carbon content at medium term, suggesting the sustainability of these silvicultural treatments.

Keywords Carbon stock · Forest floor · Mineral soil · Dead wood · Forest management · *Pinus pinaster*

Introduction

Carbon sequestration by forests provides an important mechanism for the mitigation of 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 field focuses on improving our estimation of carbon (C) stocks in the different components of forests, which are also of particular interest in terms of forest productivity (Lal 2005).

Pan et al. (2011) attempted to quantify the forest carbon sinks at global level and estimated the total stock at 861 Pg of C; comprising 383 Pg (45 %) in soil (to a depth of 1-m), 363 Pg (42 %) in above and belowground biomass, 73 Pg (8 %) in dead wood and 43 Pg (5 %) in litter. These general figures reveal that nearly 50 % of forest carbon is stored in the soil (both forest floor and mineral soil), which is therefore a significant as well as stable compartment. Current research concerning carbon stocks in forest soils and the mitigation of the effects of global change is constantly providing evidence which supports the importance

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of this compartment (Lal 2004, 2005; Jandl et al. 2007). Furthermore, soil carbon estimations for different types of Mediterranean forests also highlight the relevance of this forest compartment in the region; for example, Rodeghiero et al. (2011) in the case of Mediterranean systems, Rodriguez-Murillo (2001) and Chiti et al. (2012) for Spanish forests or Howlett et al. (2011) for agroforestry systems (dehesa).

Despite the general effort made toward improving forest carbon estimations, few studies have used an approach to total carbon stock estimation which takes into account all the forest compartments (Lecoointe et al. 2006; Nunes et al. 2010). Some studies omit elements such as coarse woody debris or mineral soil (Martin et al. 2005; Bradford et al. 2012), and they often focus just on one layer, such as plant biomass (tree, shrub or herbaceous layers) (Wirth et al. 2004; Ruiz-Peinado et al. 2011) or dead wood (logs, snags, fine and coarse woody debris) (Krankina and Harmon 1995; Herrero et al. 2010). Although such studies further our knowledge of the carbon content of forests, more complete plant and soil carbon estimations are required if we are to clearly identify the role of forests in the mitigation of global change.

Moreover, once we have determined how the carbon stocks are distributed among the different forest components, we need to identify the way in which forest management affects these stocks. Although the soil carbon stock increases at a slower rate than the biomass stock, the former is more resistant to changes in forest management (Vesterdal et al. 2002). As regards the different silvicultural treatments, regeneration felling and thinning are those which have the greatest impact on plant biomass and consequently, on the forest carbon sink. In particular, the thinning regime, length of the rotation period, specific harvesting techniques and the control of stand structure are the aspects of forest management which most heavily influence the amount of carbon in the forest (Jandl et al. 2007; Bravo et al. 2008).

The use of thinning treatments to modify stand structure and density as well as the way of harvesting trees will alter the amounts of living biomass and dead wood, change the litterfall inputs (e.g., Roig et al. 2005; Blanco et al. 2006) and influence the accumulation of organic matter (e.g., Slodick et al. 2005) by altering the micro-climate conditions in the soils, such as moisture content, temperature or biological activity. Forest floor mass decreases with thinning intensity (Vesterdal et al. 1995; Jonard et al. 2006) and sometimes this could greatly impact the carbon stock in the mineral soil. Furthermore, different harvesting methods may affect the carbon levels in the soil depending on the quantity of the fine biomass fraction which is left behind. However, Johnson and Curtis (2001) found that, in general, forest harvesting had little or no effect on soil

carbon. Even where the whole-tree method was used, no statistically significant differences were identified, although there was a small reduction in soil carbon.

Finally, species composition, soil taxonomic order and time elapsed since silvicultural operations have been found to affect the soil carbon stock (Nave et al. 2010). Therefore, experimental studies at local or regional scales are required to gain a better understanding of the way in which forest management influences the amount of carbon in forests under different environmental conditions.

In this study, we examine the effect of thinning on carbon stocks in different forest compartments to determine to what extent these silvicultural treatments positively or negatively affect the mitigation capacity of forests. We compare the carbon stocks associated with three different management options (no thinning, moderate thinning and heavy thinning) at the end of the rotation period in a reforestation of *Pinus pinaster* Ait. (Mediterranean maritime pine). This species was one of those most frequently used in the large-scale reforestation plan that was carried out in Spain during the last century, accounting for more than 800,000 hectares (Valbuena-Carabaña et al. 2010). Hence, the species currently plays an important role in carbon sequestration. The main objectives of this study are (a) to determine whether thinning treatments alter the soil carbon stocks, considering both forest floor and mineral soil; (b) to analyze the effect of thinning on the total carbon stocks of the forest; and (c) to determine the distribution of carbon in the different compartments of these pinewoods (above and belowground plant biomass, dead wood and soil).

Materials and methods

Site description

The study area is located in southern-central Spain in the Sierra Morena Mountains. The majority of forest stands in the area come from reforestations undertaken toward the middle of the last century, with *Pinus pinaster* Ait. being the most frequently used species. These reforestations were mainly carried out in degraded open woodlands of *Quercus faginea* Lamk. and *Q. suber* L. and marginal agriculture lands. Average annual precipitation in the area is approximately 790 mm, with a dry period in summer and a mean annual temperature of over 15 °C (AEMET & IM 2011). Soil type was classified as Haplic Luvisol (IUSS 2007) or Inceptisols (Soil Survey Staff 2010).

In 1984, the INIA-CIFOR set up a thinning experiment in an area reforested in 1951 by seedling. The mean elevation of the study stand is over 900 m, with slopes of 15–20 %. As the density was very high (over 5,000 trees/

ha), a pre-commercial thinning treatment was applied in 1969. The thinning experiment followed a random complete block design with three treatments and three blocks. The experiment involved the comparison of moderate thinning from below (MT) and heavy thinning from below (HT) regimes with an unthinned control treatment (CT) (Roig et al. 2005). The plots had an area of 1,000 m² (40 × 25 m). At the beginning of the experiment, the stand density was 1,394 (± SE) (68) trees ha⁻¹, with a mean basal area of 50.0 (1.2) m² ha⁻¹ and a dominant height of 15.0 (0.2) m at 33 years of age. In table 1, the main stand variables per treatment in the last inventory are presented.

Since the start of the experiment, three thinnings have been performed: in 1984, with a mean basal area reduction of 30 and 40 % (MT and HT, respectively), in 1992 (mean basal area reduction of 21 and 24 % for MT and HT) and the most recent, in 2005 (mean basal area reduction of 14 % for MT and 20 % for HT). Whole-tree harvesting was the method used in the thinning operations, removing branches and needles along with the stem from the study plots. The mean dry weight biomass remaining in the experimental plots over the whole period, expressed as a percentage of that in the CT plots, was 74 and 65 % for the MT and HT treatments, respectively. The biomass variation over the course of the thinning experiment is shown in Fig. 1.

Sampling method and carbon estimation

Soil sampling

Soil sampling was performed in the experimental plots in the late winter and early spring of 2010. Four points were chosen within each plot at a distance of 5 m from the center, at selected azimuths of 45°, 135°, 225° and 315°. At these points, the forest floor and mineral soil were sampled and pooled together by layers (forest floor) and fixed depths (mineral soil) in order to obtain a composite sample. Forest floor samples were collected in a 0.25 × 0.25 m² (0.0625 m²) metal frame quadrat and separated into three layers: litter (L), fragmented or fermentative (F) and humic (H). The L layer contained fresh needles, leaves, twigs and bark. Neither branches with a diameter >2 cm nor cones

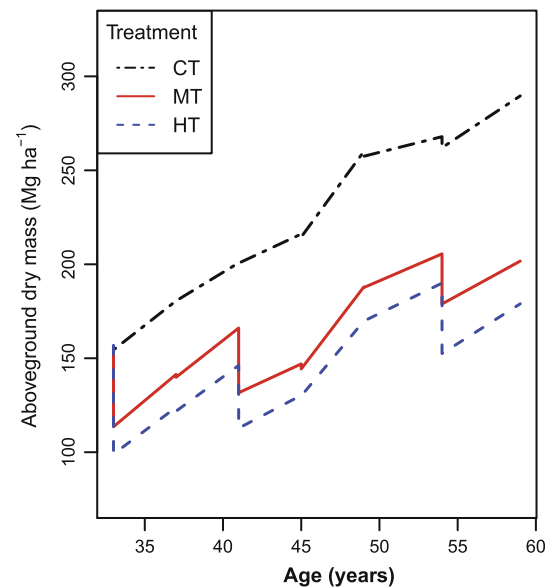


Fig. 1 Variation of the aboveground biomass (Mg ha⁻¹ of dry matter) for the different thinning treatments applied

were sampled because they were considered fine coarse debris. The F layer included litter fragments, partially decomposed. The H layer contained highly decomposed material. If the H layer was thinner than 1 cm, it was included as part of the F layer.

Mineral soil samples were taken below the four forest floor point samples up to 30 cm (Arrouays et al. 2001; Chen and Xu 2005; Rodeghiero et al. 2010) at three depth intervals (0–0.1, 0.1–0.2 and 0.2–0.3 m). A composited sample by depth and plot was used for subsequent analysis. The steel cylinder method was used to estimate the bulk density of every depth interval. A 10-cm high and 6.5-cm section cylinder was introduced vertically in one sample point of each 10-cm depth interval. For the two deepest 10-cm intervals, the upper layers were removed to avoid mixing soil sample. Some photographs of each profile were taken in order to estimate rock fragments of each depth.

Tree biomass

Plots were periodically inventoried every 4 years from 1984 to 2000 and since then every 5 years. A total of seven

Table 1 Mean stand characteristics and standard error of the experimental thinning plots of *Pinus pinaster* Ait. for the last inventory in 2010

Thinning treatment	Age (years)	Density (N ha ⁻¹)	dg (cm)	G (m ² ha ⁻¹)	Ho (m)	V (m ³ ha ⁻¹)	Wa (Mg ha ⁻¹)	Wb (Mg ha ⁻¹)
CT	59	870 ± 60	31.3 ± 1.4	67.0 ± 6.8	20.6 ± 0.6	590 ± 56	269 ± 28	61 ± 8
MT	59	427 ± 34	37.4 ± 1.2	46.6 ± 1.6	20.9 ± 0.2	433 ± 18	199 ± 8	48 ± 2
HT	59	340 ± 12	39.3 ± 0.4	41.3 ± 1.0	20.6 ± 0.6	385 ± 5	178 ± 3	45 ± 1

CT: control thinning; MT: moderate thinning; HT: heavy thinning; dg: quadratic mean diameter; G: basal area; Ho: dominant height; V: stem volume; Wa: aboveground dry weight biomass; Wb: belowground dry weight biomass

inventories have been carried out. Diameter at breast height (dbh) of all living trees was recorded and total height was measured for a sample of 30 trees per plot (representative of the diameter distribution) to estimate the mean height as well as for the 10 thickest trees per plot to calculate the dominant height. In order to estimate the height of the non-measured trees, a dbh-age-height relationship was determined for each plot.

Biomass equations for Mediterranean maritime pine developed by Ruiz-Peinado et al. (2011) were used to estimate the dry weight of the different biomass components (above and belowground) using tree dbh and height as independent variables. To convert biomass to carbon, a factor of 51.1 % (average carbon weight in wood) was applied (Ibáñez et al. 2002).

Woody debris

To assess the total woody biomass, both coarse woody debris and fine woody debris were studied. Coarse woody debris was estimated by inventorying all logs (downed woody material with a diameter >7 cm at the thickest end and longer than 0.5 m), stumps (left after cutting) and snags (standing dead trees or standing broken trees) inside the plots. Each log, stump or snag was classified according to the five-category wood decay classification of Waddell (2002) in order to apply a class reduction factor for greater accuracy in the volume/biomass calculation (Harmon and Sexton 1996). The volume of logs and snags (not broken) was calculated using the Smalian method, based on the diameter of the end sections and length. The volume of broken snags was calculated using the midpoint diameter and length (these broken snags always had a height of <5 m). The volume of stumps was estimated using the diameter at the midpoint and the stump height. Samples of wood of all decay classes were collected, and the basic density of each class was estimated through water displacement of the oven-dried samples to convert volume to biomass. Finally, the conversion factor was applied to obtain carbon weights.

The fine woody debris, defined as downed and dead woody debris of <7 cm in diameter and a minimum diameter of 2 cm, was estimated in two subplots of $3 \times 3 \text{ m}^2$ per plot. These subplots were chosen randomly within the plots. The woody material that was lower than 2 cm of diameter was considered as twigs and sampled as part of the forest floor material. Cones were considered and recorded as fine debris in these subplots, due the large cone size of Mediterranean maritime pine (length of 10–20 cm). Sampling these cones as part of forest floor material in subplots of $0.25 \times 0.25 \text{ m}^2$ could lead to an underestimation of its weight. All fine material was collected and

weighed in the field. Some subsamples were oven-dried in the laboratory to obtain the moisture content, and the conversion factor was applied to obtain the carbon weight.

Laboratory analysis

Forest floor layers were air-dried and homogenized before the analyses were performed. The L layer was separated into components (twigs, needles and bark) for optimal analysis. All samples were then weighed and subsamples oven-dried at 65 °C to constant weight in order to obtain the moisture content to convert to dry mass. The chemical analyses for organic carbon were carried out through dry combustion using a LECO HCN-600. As the H layer was not presented in all samples, we considered to join it with the data from the F layer after the chemical analysis. The carbon stock of the forest floor layers was calculated based on the carbon concentration and the dry weight of each organic layer.

Mineral soil was also air-dried and passed through a 2-mm sieve to obtain the fine fraction, on which the analyses were performed. Subsamples were oven-dried in order to calculate dry matter. Organic carbon content was obtained using a LECO HCN-600 analyzer; sand, silt and clay fractions were determined using Robinson's pipette method. Soil inorganic carbon was not detected in these samples, and for this reason, total carbon was the soil organic carbon (SOC). Rock fragments estimation was performed in the laboratory through image processing using ImageJ software (Rasband 2006). Total stoniness was calculated including the rock fragments and the soil coarse fraction.

Total carbon stocks of the mineral soil were calculated by depths using carbon concentrations, thickness of each layer, soil bulk density and stoniness at each depth, according to Eq. 1.

$$SOC_{stock} = SOC_{conc} \cdot BD \cdot L \cdot (1 - ST) \cdot 10 \quad (1)$$

where SOC_{stock} is the soil carbon stock per unit area (Mg ha^{-1} of C), SOC_{conc} is the carbon concentration in the soil sample (kg of C Mg^{-1} soil), BD is the soil bulk density (Mg soil m^{-3}), L is the depth of the sampled layer (m), ST is the stoniness of the soil (percent in mass of rock fragments >2 mm), and 10 is required to express the results in the correct units.

Statistical analysis

Differences between treatments were analyzed through mixed model analysis of variance using R software (R Development Core Team 2011) and the “lme4” package (Bates et al. 2012). The models included treatment as fixed

effects and block as random effect. The sampled carbon compartments were defined as: organic soil or forest floor, first 30 cm of mineral soil, living tree biomass (above and belowground biomass) and dead wood (snags, stumps, coarse downed and fine woody debris). If any differences were detected, a post hoc Tukey's test was applied ($\alpha = 0.05$) for pairwise comparison, using the “multcomp” package (Hothorn et al. 2008).

As mineral soil samples were collected at fixed depths in the plots, they were expected to be correlated. For this reason, they were considered repeated measures in a vertical space and depth was included as a factor (fixed effect) in the mixed model to test this influence.

Results

Soil properties

Fine soil presented a sandy loam texture with a mean sand content of 700 g kg^{-1} , a silt content of 200 g kg^{-1} and a clay content of 100 g kg^{-1} . Bulk density values increased with soil depth and mean values ranged from a minimum of 0.96 Mg m^{-3} to a maximum of 1.52 Mg m^{-3} . Stoniness was more frequent below the first 10 cm and was more or less constant at the other two depths. A greater amount of coarse fragments (41 %) were found for the HT treatment in comparison with the other two (27 and 29 % for the CT and MT, respectively). Carbon concentrations in the first 10 cm of soil were twice those found at a depth of 10–20 cm and two and a half times those detected at a depth of 20–30 cm. The C:N ratio was high (almost 30 for the 0–10 cm and 10–20 cm layers, and a slightly lower in the case of the 20–30 cm depth). The basic soil properties for the first 30 cm of mineral soil are shown in Table 2.

Soil carbon pool

The total carbon pool in the soil (including forest floor and the top 30 cm of mineral soil) was $120.45 \text{ Mg ha}^{-1}$ of C in the case of CT, $117.22 \text{ Mg ha}^{-1}$ of C for MT and $107.56 \text{ Mg ha}^{-1}$ for HT, with no significant differences between treatments.

The carbon stock found in the forest floor (L + F + H layers) showed a decreasing trend as treatment intensity increased (a reduction of 16 % for MT and 30 % for HT in relation to CT), although the treatment was not statistically significant (Table 3). This decreasing trend in carbon stock with increased thinning intensity was also observed when the data from each layer were analyzed independently (Fig. 2a). Statistically significant differences between unthinned and thinned stands were found in the case of the F + H layer.

The total carbon stock found in the first 30 cm of mineral soil varied from 90.52 Mg ha^{-1} of C for the HT stand to 96.12 Mg ha^{-1} of C for the MT, with no significant differences between treatments (Table 3). The repeated measures analysis of variance applied to evaluate whether or not there were differences according to depth and treatment revealed that depth was significant (repeated measures ANOVA, $F(2, 16) = 53.4$, $P < 0.0001$); treatment was not significant ($F(2, 16) = 0.28$, $P = 0.7613$); and there was no interaction between both factors ($F(4, 16) = 1.06$, $P = 0.4078$). The first layer of the mineral soil stored more carbon than the second (10–20 cm depth) and third (20–30 cm depth) (Fig. 2b).

Biomass carbon pool

Carbon pool in the living aboveground biomass of the Mediterranean maritime pine stands varied from $137.46 \text{ Mg of C ha}^{-1}$ for unthinned stands (CT) to

Table 2 Soil properties (mean $\pm$ standard error) for the mineral soil (0–30 cm depth) of stands by treatments

Treatment	Depth (cm)	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	Fine soil (g kg^{-1})	BD (g cm^{-3})	SOC (g kg^{-1})	C:N
CT	0–10	111 ± 16	172 ± 6	717 ± 21	843 ± 21	1.13 ± 0.02	50.1 ± 2.0	30.39 ± 1.44
	10–20	90 ± 24	199 ± 22	711 ± 37	665 ± 45	1.25 ± 0.09	27.5 ± 2.6	29.87 ± 0.97
	20–30	95 ± 19	208 ± 27	697 ± 42	670 ± 122	1.47 ± 0.11	22.7 ± 1.6	27.38 ± 1.58
MT	0–10	94 ± 4	181 ± 7	725 ± 4	841 ± 4	0.96 ± 0.05	58.6 ± 5.1	29.83 ± 0.35
	10–20	100 ± 15	234 ± 11	666 ± 25	630 ± 7	1.23 ± 0.11	35.4 ± 2.3	27.72 ± 1.88
	20–30	120 ± 32	204 ± 49	676 ± 18	673 ± 58	1.41 ± 0.03	19.7 ± 2.0	23.98 ± 1.27
HT	0–10	98 ± 6	156 ± 7	746 ± 10	700 ± 77	1.30 ± 0.17	49.6 ± 6.8	31.13 ± 0.21
	10–20	101 ± 13	202 ± 18	697 ± 29	548 ± 91	1.41 ± 0.06	24.9 ± 0.8	32.02 ± 1.16
	20–30	101 ± 18	219 ± 31	680 ± 49	522 ± 38	1.52 ± 0.04	18.6 ± 2.1	28.06 ± 0.85

CT: control thinning; MT: moderate thinning; HT: heavy thinning; BD: bulk density; SOC: soil organic carbon concentration; C:N: carbon:nitrogen ratio

Table 3 Mean carbon stocks and standard error (Mg ha^{-1} of carbon) in the living biomass, dead biomass and soil for the different compartments and treatments

Compartment/Treatment	CT	MT	HT
<i>Live aboveground tree biomass</i>	137.46 $\pm$ 14.24 a	101.65 $\pm$ 3.90 b	90.96 $\pm$ 1.68 b
Logs	3.32 $\pm$ 0.64 a	1.22 $\pm$ 0.67 b	0.65 $\pm$ 0.23 b
Stumps	0.07 $\pm$ 0.01 a	0.66 $\pm$ 0.09 b	0.63 $\pm$ 0.07 b
Snags	9.61 $\pm$ 2.08 a	1.00 $\pm$ 1.00 b	0 b
Fine woody debris	15.42 $\pm$ 1.01 a	9.99 $\pm$ 1.45 b	11.70 $\pm$ 0.28 b
<i>Total dead wood</i>	28.41 $\pm$ 2.04 a	12.87 $\pm$ 2.18 b	12.98 $\pm$ 0.37 b
<i>Live and dead aboveground biomass</i>	165.87 $\pm$ 14.93 a	114.52 $\pm$ 2.31 b	103.94 $\pm$ 1.83 b
Forest floor	24.50 $\pm$ 1.77 a	20.60 $\pm$ 3.86 a	17.04 $\pm$ 1.41 a
Mineral soil	95.95 $\pm$ 6.86 a	96.62 $\pm$ 10.82 a	90.52 $\pm$ 11.18 a
Soil	120.45 $\pm$ 5.48 a	117.22 $\pm$ 13.58 a	107.56 $\pm$ 10.61 a
Belowground tree biomass	31.01 $\pm$ 4.04a	24.73 $\pm$ 0.90 a b	22.85 $\pm$ 0.58 b
<i>Total carbon stock</i>	317.33 $\pm$ 16.69 a	256.46 $\pm$ 16.76 b	234.36 $\pm$ 9.29 b

CT: control thinning; MT: moderate thinning; HT: heavy thinning

90.96 Mg of C ha^{-1} for HT stands, with significant differences between the control plots and the thinned ones (Table 3). Carbon stored in the dead wood also decreased with the thinning intensity, from 28.41 Mg ha^{-1} of C for CT to 12.98 Mg ha^{-1} of C for HT stands, and again, there were significant differences between the control and thinned stands, although not between the two thinning treatments. The largest compartment of dead wood was the fine woody debris (fine wood and pine cones) in all cases.

Carbon pools in the aboveground biomass (considering the living and different compartments of dead wood) for the CT stand were always greater than for thinned stands, with the exception of the carbon stored in stumps. However, there were no statistical differences between the two thinning treatments, even though the carbon pool in living aboveground biomass was greater for MT than for HT (Table 3).

When total living biomass was considered, including above and belowground biomass, a similar decreasing trend was also observed (Table 3).

Total carbon pools

Total carbon stock of the MT stand (including living aboveground biomass and dead wood, belowground tree biomass, forest floor and the uppermost 30 cm of mineral soil) was 19 % lower than the CT stand, while the drop in total carbon in the case of the HT stand was 26 % (Fig. 3). The carbon stock associated with the thinning stands was significantly different from that of the control treatment (CT), although the MT and HT treatments were not statistically different.

Discussion

Soil carbon stock

From the analysis of the soil data, we can affirm that the tested thinning intensities did not significantly affect the carbon stock in the soil (forest floor and first 30 cm of the mineral soil), despite a whole-tree harvesting method was used and there were no inputs to the plots from harvest slash. These results agree with the findings of meta-analysis studies by [Johnson and Curtis \(2001\)](#), which revealed that harvesting generally has little or no effect on the carbon stock in the soil as a whole, although they identified differences between various harvesting techniques and reported that whole-tree harvesting led to a small reduction of 6 % in the carbon stock of the A horizon. However, in another study undertaken by [Nave et al. \(2010\)](#), the authors found that forest management (including thinning and final cuttings) reduced the amount of carbon in soil by a small but significant amount (8 %), with several sources of variation.

Concerning the carbon stock in the uppermost 30 cm of mineral soil, the lack of significant differences between management practices has also been reported in a number of studies ([Johnson and Curtis 2001](#); [Jones et al. 2008](#); [Chatterjee et al. 2009](#)). However, the soil order could have an influence on the changes in the carbon pool of the mineral soil ([Nave et al. 2010](#)). These authors found that in the case of Inceptisols (the same soil order as that present in our stand), the time elapsed since harvesting was the principal source of variation. The carbon loss is temporary and recovers over a period of 6–20 years after harvesting. Consequently, it is possible that some temporal differences between treatments may have already existed, but due to

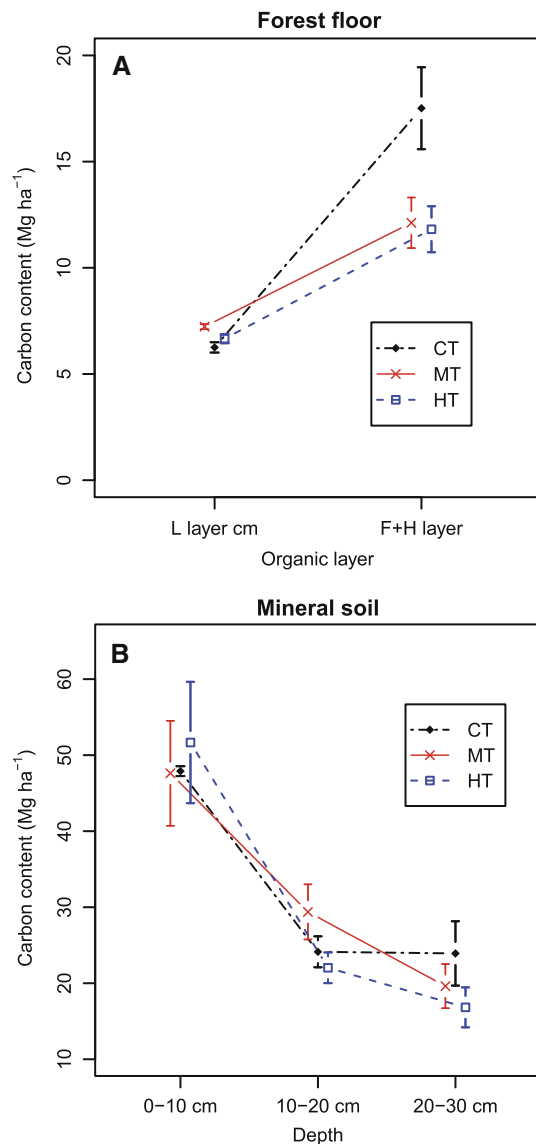


Fig. 2 Mean values of carbon stocks (Mg ha⁻¹ of C) for the different treatments considered by layers for the forest floor (a) and depths for the mineral soil (b)

the absence of continuous monitoring, such differences may not have been identified. As the rotation time between thinning operations was equal or greater than 8 years, this time period could be sufficient to allow the soil carbon stocks to recover from the potential loss. Moreover, the soil sampling for the purposes of the study was carried out 5 years after the last silvicultural intervention, this last thinning being the lightest of the three treatments applied (mean basal area reduction of 14 % for MT and 20 % for HT).

It is also assumed that forest management has different effects on the forest floor and the mineral soil. Nave et al. (2010) showed that carbon stocks in the forest floor are more vulnerable to changes associated with harvesting (a significant mean reduction of 30 %), the largest differences

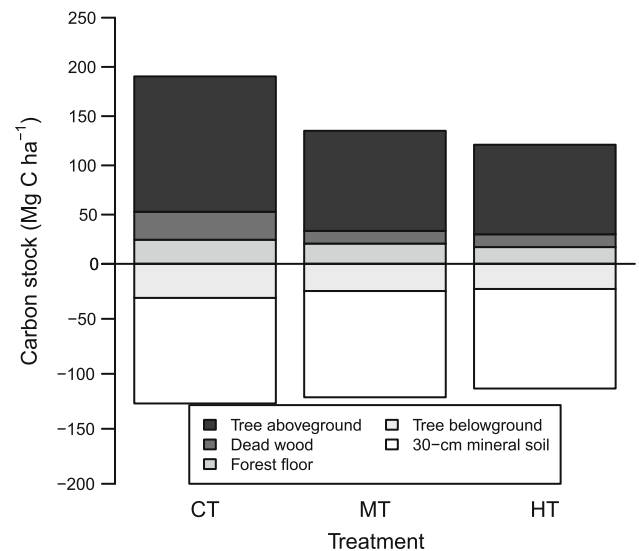


Fig. 3 Above and belowground carbon stocks (Mg ha⁻¹ of C) for the different pools considered

being those related to species composition (conifer/mixed around -20 %). However, in our study, no statistically significant differences in the carbon stock of the forest floor layer were identified between stands with different thinning treatments, although a decrease in carbon stock with increasing thinning intensity was detected (mean reduction of 16 and 30 % for MT and HT treatments, respectively, in relation to the forest floor carbon stock of the CT) as reported by other authors (Vesterdal et al. 1995; Jones et al. 2008; Nilsen and Strand 2008). In relative terms, these are substantial reductions due to the small size of the forest floor carbon pool (in relation to the mineral soil); hence, small changes in absolute terms can mean important changes in relative terms. Several factors could explain the observed decrease in forest floor carbon stocks when thinning intensity increases, such as reduced litterfall input after the thinning operations. At the same experimental site, Roig et al. (2005) reported changes in litter production as a result of thinning, but the effects disappeared 5 years after treatment due to tree and crown growth. This temporal effect observed for litterfall would appear to support the above-mentioned hypothesis that temporal effects of thinning on soil carbon (mainly in forest floor) may have existed but have not been captured by the study (Yanai et al. 2000). The decrease in the carbon stock of the forest floor as a result of thinning (Table 3) may also be due to an increase in decomposition rates caused by changes in the moisture levels and temperature of the soil surface, or to higher CO₂ output and the mixing of organic matter into the mineral soil during the harvesting process (Jonard et al. 2006). Hence, the amount of carbon in the F + H layer of the unthinned plots was significantly greater than in the same layer of the thinned plots (Fig. 2a).

The C:N ratio has commonly been used as an indicator of the degree of decomposition and of the quality of the organic matter held in the soil (Batjes 1996). It has also been used as an indicator of carbon sequestration in soils (Vesterdal et al. 2008), although, in the case of the soil samples examined in the present study, no differences were found between the C:N ratios of the thinning treatments (at least at the end of the rotation period). The high C:N ratios found in the mineral soil indicate a low degree of decomposition of the organic matter, dominated by stable carbon forms consistent with its litterfall origin (Díaz-Pinés et al. 2011).

The soil carbon pool (forest floor and mineral soil) of the studied stands was similar to that found for stands of other species under similar climatic conditions, such as that reported by Charro et al. (2010) and Díaz-Pinés et al. (2011) for *Pinus sylvestris* stands in Central Spain (between 85 and 130 Mg ha⁻¹ of C). In the case of *P. pinaster* (subsp. *atlantica*) in southwestern France, a broader range was registered depending on the site (58–203 Mg ha⁻¹ of C), from dry dune sites to wet moorland sites where the greatest stocks were found (Augusto et al. 2010).

Biomass and dead wood carbon

Total dead wood carbon stocks in the thinned plots were 45 % of those in the unthinned plots, with fine woody debris (fine wood and pine cones) comprising the largest compartment in all cases. As regards coarse woody debris (logs, stumps and snags), the thinned plots contained 17 % (MT) and 5 % (HT) of the amount present in the CT. These values agree with estimates that the quantity of coarse woody debris in managed forest is between 2 and 30 % that of unmanaged forest (Fridman and Walheim 2000). These figures also depend on the harvest method used; stands with whole-tree harvest have less downed wood that stands with stem-only harvest do (Rittenhouse et al. 2012). In the Mediterranean region, the amount of slash is frequently reduced during thinning operations in order to reduce the risk of forest fire, although this compartment plays an important role in ecological processes. The stump compartment in the studied stands is 5 % of the total dead wood carbon. Despite the greater number of stumps measured in the HT treatment, they accounted for less carbon than in the MT treatment because the former were in a higher decay class. Additionally, in the HT treatment, mortality is controlled by thinning and snags are not present, only some logs were left on the floor.

Differences in total carbon stock between unthinned and thinned stands in the study are largely due to the amount of biomass (living and dead wood) in the stands, as reported in other studies concerning the effects of management on

carbon storage (e.g., Skovsgaard et al. 2006; Chatterjee et al. 2009; Jurgensen et al. 2012). The relative absence of differences between the two thinned stands (MT and HT) is probably due to the fact that there was little difference between the thinning intensities, as evidenced by the mean post-treatment aboveground biomass in the thinned stands relative to the control treatment (74 % in the case of MT and 65 % for HT). The dead wood component also contributed to the differences in the total carbon content, the reduction in this component clearly being attributable to management, as reported in other studies (Krankina and Harmon 1995; Nilsen and Strand 2008).

Distribution of carbon stocks

The most important carbon pool identified in the studied plots was tree biomass (53, 50 and 49 %, respectively, for the CT, MT and HT), which included above and below-ground biomass (Fig. 3). The next largest was the mineral soil pool (top 30 cm in this case) which accounted for 30, 38 and 39 % for the CT, MT and HT, respectively. Finally, forest floor carbon stocks varied between 9 % (CT) and 5 % (MT), and dead wood carbon pool values comprised between 8 % (CT and MT) and 7 % (HT). These general percentages obtained are relatively close to those general figures given by Pan et al. (2011) for global forest carbon stocks (~50 % of C in soil and 50 % of C in living biomass and dead wood). In our study, the proportions of total carbon in soil were lower, although it is important to consider that the studied stands belong to reforestation of degraded open woodlands and marginal agricultural lands with lower soil carbon stock than natural forests and we considered the uppermost 30 cm of mineral soil.

The total amounts of carbon found in our experiment (317.33–234.36 Mg ha⁻¹ of C) were very similar to those presented by Nunes et al. (2010) for different maritime pine (subsp. *atlantica*) stands in Portugal. These authors used similar carbon compartments in their study and found a decreasing trend in total carbon stocks along an altitudinal and precipitation gradient (from northern to southern Portugal). Total carbon stocks were found to vary from 308.6 Mg ha⁻¹ of C in the wettest and highest location to 100.6 Mg ha⁻¹ in the least humid and lowest location at a mean age of 36 years.

Although significant differences were found in carbon stocks for the living aboveground biomass between the treatments, it must be borne in mind that in the thinned plots, a large amount of carbon was removed through silvicultural activities. Over the three interventions, a total of 116.87 (15.94) Mg ha⁻¹ of C was removed from the MT stand and 145.11 (7.90) Mg ha⁻¹ from the HT stand. If we take into account these biomass extractions, total carbon in aboveground biomass (living + dead + extracted by

thinning) was 165.87 (14.93) Mg ha⁻¹ of C in the case of the CT stand, 231.39 (18.20) Mg ha⁻¹ for the MT and 249.05 (6.08) Mg ha⁻¹ for the HT, with differences between unthinned and thinning treatments. These differences found in total carbon between managed and unmanaged stands highlight the importance of forest management on the mitigation effects. So, the in situ carbon stocks are not the only relevant indicators for carbon sequestration because harvested biomass (including biomass in wood products or for substitution of fossil fuel) can contribute as an important amount to carbon sequestration in managed forests.

Conclusions

The results of this study in a Mediterranean pinewood reveal that the application of thinning treatments does not alter the carbon content either of the forest floor material or the mineral soil, even though a whole-tree harvesting method was used. This fact could be of great importance for the management of this kind of reforestation. In the first place, results suggest that under the thinning regime described, the soil carbon stocks are not compromised in the medium term. Furthermore, results are endorsing the sustainability of this kind of management applied in this reforestation, at least from a decadal perspective and from the point of view of carbon stocks in biomass, dead wood and soil. Secondly, since the differences between carbon stocks from one treatment to the other were only found for plant biomass (in situ and harvested), these components can be used as indicators of total carbon stocks in order to compare different silvicultural alternatives as measures for mitigating global change, particularly if we consider that the tree biomass was the largest carbon pool found in this Mediterranean forest system.

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