Mitig Adapt Strateg Glob Change (2016) 21:1059–1072
DOI 10.1007/s11027-014-9585-0

ORIGINAL ARTICLE

'Carbon stocks in a Scots pine afforestation under different thinning intensities management'

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Received: 30 August 2013 / Accepted: 2 June 2014 / Published online: 13 June 2014

Abstract Thinning, as a forest management strategy, may contribute towards mitigating climate change, depending on its net effect on forest carbon (C) stocks. Although thinning provides off-site C storage (in the form of wood products) it is still not clear whether it results in an increase, a reduction or no change in on-site C storage. In this study we analyze the effect of thinning on C stocks in a long-term experiment. Different thinning intensities (moderate, heavy and unthinned) have been applied over the last 30 years in a Scots pine (*Pinus sylvestris* L.) stand, with a thinning rotation period of 10 years. The main C compartments were analyzed: above and belowground tree biomass, deadwood, forest floor and upper 30-cm of the mineral soil and tree biomass removed in thinning treatments. The results revealed that unthinned stands had the highest C stocks with 315 Mg C ha^{-1}, moderate thinning presented 304 Mg C ha^{-1} and heavy thinning 296 Mg C ha^{-1}, with significant differences between unthinned and heavily thinned stands. These differences were mainly due to C stock in live biomass, which decreased with thinning intensity. However, soil C stocks, forest floor and mineral soil, were not influenced by thinning, all of the stands displaying very similar values 102–107 Mg C ha^{-1} for total soil; 15–19 Mg C ha^{-1} for forest floor; 87–88 Mg C ha^{-1} for mineral soil). These results highlight the sustainability of thinning treatments in terms of C stocks in this pinewood afforestation, and provide valuable information for forest management aimed at mitigating climate change.

Keywords Aboveground biomass · Carbon sequestration · Forest management · Mitigation · *Pinus sylvestris* · Soil carbon stock

1 Introduction

Maintaining carbon (C) stocks and enhancing growth in existing forests are key aspects of sustainable forest management strategies aimed at mitigating the effects of climate change.

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Moreover, reducing deforestation, increasing the use of forest products or creating new forests through forestation (reforestation and afforestation) are also critical to the removal of carbon dioxide (CO_2) from the atmosphere (Nabuurs et al. 2007). As regards the latter of these initiatives, the impact of national forestation programs on C sequestration is notably positive (e.g., Fang and Wang 2001; Kaul et al. 2010), especially when forests replace marginal agricultural lands (Jandl et al. 2007). The benefits of such policies are particularly evident in Spain, where around 4 million hectares of newly forested areas (both afforested and reforested from 1940 to 2006 (SECF 2011)) play an important role as C sinks (Padilla et al. 2010; Herrero and Bravo 2012; Pérez-Cruzado et al. 2012).

The growth of these new forests leads to C sequestration both in the tree biomass and in the soils. Live biomass C is a forest compartment which grows rapidly during the first years following afforestation. However, soil C increases slowly (Post and Kwon 2000) and sometimes the short-term effects are negligible due to the C stock decrease in the first years and further recovery (Paul et al. 2002). Nevertheless, it is important to note that the soil C stock is a long-lived pool (Lal 2004a).

The C accumulation rates in biomass and soil could be increased through different forest management strategies, such as adapting the composition of forest species, employing longer rotation periods, soil conservation or thinning (Bravo et al. 2008). Thinning treatments aimed at achieving silvicultural objectives also aid in the mitigation of and adaptation to the impacts of global change by enhancing forest C stores and by maintaining high levels of compositional, functional and/or structural complexity (D'Amato et al. 2011). Furthermore, it has been suggested that C storage in wood products could provide a more viable long-term climate mitigation strategy than on-site sequestration (Niles and Schwarze 2001; Valsta et al. 2008), depending, among other factors, on site productivity and conditions to enable products to be harvested and used efficiently (Marland et al. 1997).

In many of the abovementioned reforested areas of Spain, little or no silvicultural interventions have been applied. Therefore, these forests currently display a high degree of homogeneity as well as high densities, and urgently require the application of thinning treatments to ensure their viability as providers of goods and services, including their function as C sinks. In this paper we investigate the influence of thinning on forest C stocks through a long-term research trial in which forest management has been applied over 30 years, in order to determine whether these activities affect the mitigation capacity of the afforestation. The trial was carried out in a *Pinus sylvestris* L. afforestation, which is currently mid-way through the rotation period. This species was one of the most commonly used in the Spanish plantation program, accounting for over 0.6 million hectares (Valbuena-Carabaña et al. 2010). The specific objective of the study was to evaluate the effect of different thinning intensities (moderate and heavy), in comparison to unthinned stands, on the C stocks in the different forest compartments: i) above and belowground tree biomass; ii) deadwood; iii) soil, forest floor and mineral soil; and iv) tree biomass harvested in thinning operations.

2 Material and methods

2.1 Study area

The area is situated in the 'Sierra de la Demanda' mountains (Burgos, Spain) (42° 19′N – 3° 21′ W). The main forested areas consist of *Pinus sylvestris* L. afforestations established on marginal agricultural lands in the middle of the last century, and natural forests of *Quercus pyrenaica* Willd. The climate is characterized by mean annual precipitation of 959 mm with a dry period in summer, mean annual evapotranspiration of 600 mm and mean annual temperature of 9.2 °C (MAGRAMA 2013). The soil type is defined as Humic Cambisol (IUSS 2007).

2.2 Experimental design

The experiment is located in an afforestation dating from 1960, established on marginal agricultural land in an area with a mean elevation above 1200 m and which is flat or gently sloping (slopes <5 %). The initial density of the afforestation was about 1800 trees ha^{-1}. The site index of the stand is 18 m at a reference age of 50 years (Río et al. 2006), being classified as an intermediate site quality. When the stand was 22 years old (1982), the thinning trial was set up in order to compare the effect of thinning intensity on forest growth and yield. The experiment involved three treatments: moderate thinning (*M*), heavy thinning (*H*) and unthinned or control treatment (*U*), using a randomized complete block design with three blocks. Plot size was 1000 m^2 (40 m length and 25 m width), with a 10-m wide buffer.

Three thinning from the lower end of the diameter distribution (thinning from below) operations were performed over the study period with a thinning rotation of 10 years: 1982, 1992 and 2002. For the *M* treatment, the mean basal area reduction in relation to the unthinned treatment was 11 % for the first thinning (mean residual basal area of 22.4 m^2 ha^{-1}), 18 % for the second thinning (residual basal area of 34.8 m^2 ha^{-1}) and 31 % for the third thinning (residual basal area 39.5 m^2 ha^{-1}). For the *H* treatment, the mean basal area reductions in the three thinning operations in comparison to the control treatment were 22 % (residual basal area of 19.6 m^2 ha^{-1}), 31 % (residual basal area of 29.3 m^2 ha^{-1}) and 44 % (residual basal area of 32.2 m^2 ha^{-1}). In the *U* treatment, where the plots were not thinned except for the removal of snags, mean basal areas of 25.2, 42.5 and 57.2 m^2 ha^{-1} were recorded in the respective thinning years. Stem-only harvesting was the method used in all thinning operations. Logging residues were chipped and left on the forest floor following harvesting.

2.3 Data collection

2.3.1 Tree biomass

Seven inventories have been carried out since the experiment was established; these being performed every 5 years (the last was conducted in 2012). Measurements included diameter at breast height (dbh) of all trees and total heights of 30 trees per plot sampled along the diametric distribution to estimate mean height and of the 10 thickest trees per plot to calculate the dominant height. Missing height measurements were computed using a height-diameter mixed-effects model (Robinson and Wykoff 2004).

Above and belowground biomass were estimated using tree biomass models developed by Ruiz-Peinado et al. (2011) based on tree dbh and total height. To convert biomass dry weight to C weight a mean value of 50.9 % was used (Ibáñez et al. 2002). The main stand variables by treatment for the first (1982) and last inventory (2012) are presented in Table 1.

2.3.2 Deadwood

All compartments of deadwood (coarse and fine woody debris) were sampled in the trial plots in 2012. Biomass in the form of coarse woody debris, including logs (downed woody material with a diameter larger than 7 cm at the thickest end), snags (standing dead trees) and stumps, was estimated by inventorying all the dead material in the plots. In the case of logs, end-section diameters and length were recorded to calculate volume using the Smalian method; snag

Table 1 Stand characteristics (mean±standard error) by treatment for the first (1982) and last (2012) inventory

Inv	Thinning treatment	Age (years)	Density (N ha^{-1})	Ho (m)	dg (cm)	G (m^2 ha^{-1})	Volume (m^3 ha^{-1})	Biomass (Mg ha^{-1})
1982	Unthinned	22	1623±49	8.8±0.1	14.1±0.5	25.5±1.3	93.6±5.5	78.7±4.6
	Moderate	22	1653±19	8.3±0.6	13.9±0.3	25.1±1.3	90.2±4.8	77.1±4.1
	Heavy	22	1723±41	9.4±0.2	13.7±0.3	25.5±1.8	90.9±5.6	78.1±5.8
2012	Unthinned	52	1460±81	17.7±0.3	24.5±0.4	68.7±2.4	474.5±8.9	266.1±7.4
	Moderate	52	780±17	17.8±0.3	28.8±0.4	50.7±0.3	375.6±5.0	206.9±2.6
	Heavy	52	590±44	17.2±0.2	30.7±0.8	43.3±1.1	321.2±7.6	177.8±4.3

Inv inventory, *Ho* dominant height, *dg* quadratic mean diameter, *G* basal area, *Biomass* Aboveground biomass

biomass was calculated using the biomass equations developed by Ruiz-Peinado et al. (2011) using dbh and height data but excluding twig fraction; and finally, stump volume was calculated using the midpoint diameter and length. Each item was classified into five wood-decay categories (Waddell 2002) to further improve the biomass estimation, using a reduction factor in the calculations. Samples of each wood-decay class were taken to the laboratory to obtain the basic wood density through volumetric methods to estimate the reduction factors.

In each plot, fine woody debris including all downed and dead material with an end diameter of between 2 and 7 cm was collected and weighed in three square, randomly located subplots of 4×4 m^2. Bark and woody material with a diameter of less than 2 cm were included in the forest floor compartment. Fine woody debris samples were taken to the laboratory to determine the moisture content and then estimate dry mass.

For all woody debris classes, the C content value applied was the same as that used in biomass estimations.

2.3.3 Soil data

Soil sampling was carried out in autumn 2010, 8 years after the third thinning, at the stand age of 50 years. In each plot, four sampling points were located systematically at a distance of 5 m from the plot center at selected azimuths of 45°, 135°, 225° and 315°, where forest floor and mineral soil were sampled. Forest floor was collected using a metal frame of 0.25×0.25 m^2 and then separated into layers: litter (L), which included fresh and non-decomposed material, fragmented (F) consisting of partially decomposed though well recognizable material, and humic (H) comprising highly decomposed organic material (van Delft et al. 2006). The thickness of each layer was also recorded. As the H-layer was thinner than 1 cm it was joined with the F-layer (FH-layer). A composite sample per layer and plot was made from the four sampling points. Samples were oven-dried at 65 °C in the laboratory, weighed and examined through dry combustion using a LECO CHN-600 analyzer to determine the organic C content. The C stock of the forest floor was computed through the C concentration and the dry weight of each layer.

Samples of mineral soil were collected at the same points as the forest floor samples. The soil samples were taken from the upper 30-cm, considering three depth intervals (0–0.1, 0.1-0.2 and 0.2-0.3 m). The samples corresponding to each depth were taken from holes excavated for this purpose. In each plot, a composite sample from the four points was made per sampling depth and then oven-dried in the laboratory at 65°C. Bulk density was estimated for each depth using the cylinder method, whereby a steel cylinder 10-cm high and 6.5-cm in diameter was inserted vertically to extract a non-disturbed sample of mineral soil, the weight of which was then recorded. The following basic properties were analyzed: stone content was determined by passing subsamples of soil through a 2-mm sieve; texture (sand, silt and clay) was analyzed using Robinson's pipette method; C concentration was determined using a LECO CHN-600 analyzer. No inorganic carbon ($CaCO_3$) was found in the mineral soil, all C being considered organic C.

The total organic C in the mineral soil was calculated using the following equation

$$SOC_{stock} = \sum_{depth\ i=1}^{depth\ n} SOC_{con\ i} \cdot BD_i \cdot d_i \cdot (1 - ST_i) \cdot 10$$

Where SOC_{stock} is the soil carbon stock (Mg C ha^{-1}), $SOC_{con\ i}$ is the carbon concentration at depth i (kg C Mg^{-1} soil), BD_i is the soil bulk density for depth i (Mg soil m^{-3}), d_i is the thickness of depth i (m), ST_i is the stone fraction for depth i; and 10 is the need to express results in the correct units.

2.4 Data analysis

Mixed model analysis of variance was used to identify differences in treatment effects, considering treatment as a fixed effect and block as a random effect. R software (R Development Core Team 2013) and the 'lme4' package (Bates et al. 2013) were used in this analysis. When differences were detected, a post-hoc analysis using the 'multcomp' package (Hothorn et al. 2008) was applied for pairwise comparison. Statistical significance was at the 0.05 level.

As forest floor and mineral soil samples were collected at the same place and at fixed depths (vertical space) we expected the C measurements by depth (concentrations and stocks) to be correlated. Analyses of these data were conducted through a repeated measures analysis of variance (RMANOVA) using a mixed model and including depth as a fixed effect.

3 Results

3.1 Tree biomass C stocks

The C stock in aboveground tree biomass differed significantly among the treatments (Table 2). In the *U* treatment, it was significantly higher (135 Mg C ha^{-1}) than in the *M* treatment (22 % lower than unthinned) and the *H* treatment (33 % lower than *U* and 14 % lower than *M*). Similarly, the C stock in the belowground biomass pool also decreased with the intensity of the thinning regime, with a mean value of 58 Mg C ha^{-1} for *U* and a mean reduction of 26 % for *M* and 34 % for *H*, although significant differences were only identified between unthinned and managed stands (Table 2). The total living tree biomass C pool at the time of the last sampling was 193 Mg C ha^{-1}, 148 Mg C ha^{-1} and 128 Mg C ha^{-1} for *U*, *M* and *H* treatments respectively. The differences among treatments were statistically significant ($p<0.05$). The C stock removed over the three interventions was 3 Mg C ha^{-1} for *U* (snags were felled and extracted), 34 Mg C ha^{-1} for *M* and 44 Mg C ha^{-1} for *H*. When considering total C stocks (living biomass C plus C removed in thinning operations) there were significant differences between unthinned and thinned treatments (196 Mg C ha^{-1} for *U*, 182 Mg C ha^{-1} for *M* and 172 Mg C ha^{-1} for *H*).

Table 2 Carbon stocks (mean±standard error) for the different thinning treatments and compartments

	Thinning treatment		
Carbon (Mg C ha^{-1})	Unthinned	Moderate	Heavy
Tree biomass	193.3±4.7 a	148.1±1.3 b	128.5±3.6 c
Aboveground biomass	135.4±3.1 a	105.3±1.1 b	90.5±1.8 c
Belowground biomass	57.8±1.6 a	42.7±0.2 b	38.0±1.8 b
Removed aboveground biomass	3.1±0.6 a	33.7±1. 8 b	43.9±2.9 c
Total deadwood	13.5±0.4 a	15.9±2.4 ab	21.3±1.0 b
Logs	0.6±0.2 a	0.1±0.0 a	0.2±0.1 a
Stumps	0.0±0.0 a	0.2±0.0 b	0.3±0.0 c
Snags	0.8±0.1 a	0.0±0.0 a	1.1±0.9 a
Fine woody debris	12.1±0.3 a	15.6±2.4 ab	19.6±0.9 b
Soil	105.6±6.4 a	106.6±4.1 a	102.1±5.6 a
Forest floor	17.4±1.7 a	19.3±1.2 a	14.7±0.7 a
30-cm Mineral soil	88.2±8.0 a	87.2±4.8 a	87.4±5.7 a
Total carbon stock (on-site)	312.4±2.4 a	270.6±4.1 b	251.9±7.6 b
Total (on-site) + Removed	315.5±2.1 a	304.3±5.9 ab	295.8±4.8 b

Different letters show statistical significant differences between thinning treatments

3.2 Deadwood C stock

Total deadwood in the *U* treatment was 13.5 Mg C ha^{-1}, with mean values of 90 % in the form of fine woody debris, 6 % snags and 4 % logs; total deadwood in the *M* treatment stands amounted to 15.9 Mg C ha^{-1} with 98 % in the form of fine woody debris, 2 % stumps and 1 % logs; and finally, in the *H* treatment stands there was a total of 21.3 Mg C ha^{-1} with 92 % in the form of fine woody debris, 5 % snags, 1 % stumps and 1 % logs (Table 2). We identified significant differences between the *U* and *H* treatments for total deadwood, mainly due to the fine woody debris component.

3.3 Soil C stocks

3.3.1 Forest floor

The thickness of the L-layer and FH-layer of the forest floor were not statistically different between the treatments considered. These varied between 1.7 and 1.9 cm for the L-layer and 2.2 and 2.7 cm for the FH-layer. Thus, the depth of the forest floor layer was between 3.9 and 4.6 cm.

The forest floor bulk density was also not significantly different among the thinning intensities tested (Table 3). The lowest density in the L-layer was found for the *U* treatment (43 kg m^{-3}) and the highest value for the *M* treatment (60 kg m^{-3}). In the FH-layer, bulk densities were substantially higher, varying from 128 kg m^{-3} for the *H* treatment to 149 kg m^{-3} for the *U* treatment.

The C concentration on the forest floor ranged from 51 to 52 % in the L-layer to 38-42 % in the FH-layer (Table 3), with no significant differences between treatments.

The C stocks found on the forest floor were 17.4 Mg C ha^{-1} for the *U* treatment, 19.3 Mg C ha^{-1} for the *M* treatment and 14.7 Mg C ha^{-1} for the *H* treatment (Table 2). Similarly, there

Table 3 Bulk density, carbon concentration and soil texture values (mean±standard error) by thinning treatment

Parameter		Soil	Layer	Thinning treatment		
				Unthinned	Moderate thinning	Heavy thinning
Bulk density (kg m^{-3})		Forest floor	L	43 a (6)	60 a (6)	47 a (11)
			F+H	149 b (27)	128 b (12)	130 b (17)
		Mineral soil	0–10 cm	1155 (31)	1030 (24)	1305 (40)
			10–20 cm	1420 (28)	1500 (52)	1380 (19)
			20–30 cm	1395 (12)	1580 (5)	1475 (35)
SOC concentration (g kg^{-1})		Forest floor	L	519.8 a (0.7)	511.2 a (2.9)	511.5 a (2.9)
			F+H	423.7 b (26.3)	386.0 b (3.3)	382.4 b (6.7)
		Mineral soil	0–10 cm	42.3 a (1.8)	45.6 a (1.6)	36.5 a (3.4)
			10–20 cm	25.8 b (3.0)	26.4 b (2.7)	22.7 b (0.8)
			20–30 cm	18.4 b (2.3)	17.4 b (1.2)	20.1 b (2.2)
Texture	Clay (%)	Mineral soil	0–10 cm	14.2 (0.5)	14.4 (1.0)	14.3 (0.4)
	Silt (%)			35.9 (0.8)	39.9 (0.8)	38.6 (0.9)
	Sand (%)			49.9 (1.2)	45.7 (0.3)	47.1 (1.1)
	Clay (%)		10–20 cm	14.6 (0.7)	13.9 (1.2)	13.8 (0.4)
	Silt (%)			33.6 (1.5)	36.1 (2.0)	33.6 (0.6)
	Sand (%)			51.8 (1.9)	50.0 (2.7)	52.6 (0.8)
	Clay (%)		20–30 cm	17.7 (3.0)	14.8 (1.2)	16.0 (1.3)
	Silt (%)			35.9 (1.7)	34.3 (0.1)	32.4 (0.7)
	Sand (%)			46.4 (1.7)	50.9 (1.2)	51.6 (1.5)

L litter layer of the forest floor, *F+H* fragmented and humic layers of the forest floor, *0–10 cm*, *10–20 cm*, *20–30 cm* considered depths in the mineral soil. Different letters show statistical significant differences ($P<0.05$) in the comparison between layers

were no significant differences between treatments. Considering the forest floor layers as repeated measures in vertical space for the identification of differences between layers and treatments using RMANOVA (Table 4), the treatments were not statistically different, the layer was significant and the interaction between both factors was not significant. The FH-layer was found to be accumulating between 2.4 and 3.7 times more C than the L-layer (Table 5).

3.3.2 Mineral soil

A loam texture was found at all samples sites, with a mean sand content of 49.5 %, a clay content of 14.9 % and a silt content of 35.6 % in the fine soil (Table 3). Mean stoniness was higher in the 10–20 cm depth sample (38±3 %) and statistically different from the values at the other depths considered (17±4 % for the 0–10 cm depth and 25±4 for the 20–30 cm depth).

The analysis of variance (RMANOVA) applied to evaluate whether differences existed in bulk density according to depth of layer and treatment revealed that depth was significant ($F(2,16)=63.84$, $P<0.0001$), treatment was not significant ($F(2,16)=2.32$, $P=0.1302$) and the interaction term between depth and treatment was significant ($F(4,10)=10.08$, $P=0.0003$). Bulk density values increased with soil depth, except in the unthinned stands where the 20–30 cm bulk density value was lower than for the 10–20 cm depth (Table 3).

The C concentration analysis, considering both depth and treatment, did not reveal differences between the treatments applied ($F(2,16)=1.36$, $P=0.2554$). Depth was the relevant

Table 4 Two-way RMANOVA testing if (A) thinning treatment or forest floor layer influenced forest floor carbon stocks; (B) thinning treatment or soil depth influenced mineral soil carbon stocks

Effect	Df	MS	F	P
(A) Forest floor				
Thinning treatment	2	3.64	0.742	0.497
Forest floor layer	1	298.73	60.857	<0.0001***
Thinning treatment X Forest floor layer	2	1.20	0.245	0.787
Error	12	4.91		
(B) Mineral soil				
Thinning treatment	2	0.84	0.0217	0.979
Soil depth	2	1228.84	31.666	<0.0001***
Thinning treatment X Soil depth	4	21.03	0.542	0.722
Error	16	40.4		

Df degrees of freedom, *MS* mean square, *F* F value, *P* p value

*** Significant value

factor ($F(2,16)=60.73$, $P<0.0001$), the C concentration decreasing with soil depth (Table 3), and the interaction between depth and thinning treatment was not significant ($F(4,16)=1.32$, $P=0.3047$).

Total C stocks found in the upper 30-cm of mineral soil amounted to 87–88 Mg C ha^{-1} (Table 2). In this case, treatment was not significant, depth was significant and there was no interaction between the two factors (Table 4). Statistically significant differences were found between the C stock at the first depth (0–10 cm depth) and the other depths (10–20 cm and 20–30 cm).

3.4 Total C stock and distribution

Total on-site C accounted for 312 Mg C ha^{-1}, 271 Mg C ha^{-1} and 252 Mg C ha^{-1} for the *U*, *M* and H thinning treatments respectively, indicating differences between unthinned and thinned stands (Table 2). There was a 13 % reduction in the on-site C stock for the *M* treatment and a 19 % reduction in the case of the *H* treatment in comparison with the unthinned stand.

When the C compartment for the biomass harvested in the three thinning operations (off-site) was included, differences were found between the *U* and *H* treatments (315 Mg C ha^{-1} for *U* while the *M* and *H* treatments presented 96 % and 94 % respectively of the C stock in control plots) (Fig. 1).

Table 5 Comparison of mean carbon stocks by layer/depth for each thinning treatment

Thinning treatment	Forest floor C stock (Mg C ha^{-1})		Mineral soil C stock (Mg C ha^{-1})		
	L layer	F+H layer	0-10 cm	10-20 cm	20-30 cm
Unthinned	3.7 a	13.7 b	40.4 a	26.8 b	21.7 b
Moderate	5.7 a	13.7 b	43.0 a	24.6 b	19.7 b
Heavy	4.2 a	10.5 b	42.7 a	21.0 b	22.2 b

Different letters show statistical significant differences ($P<0.05$) between layer/depth

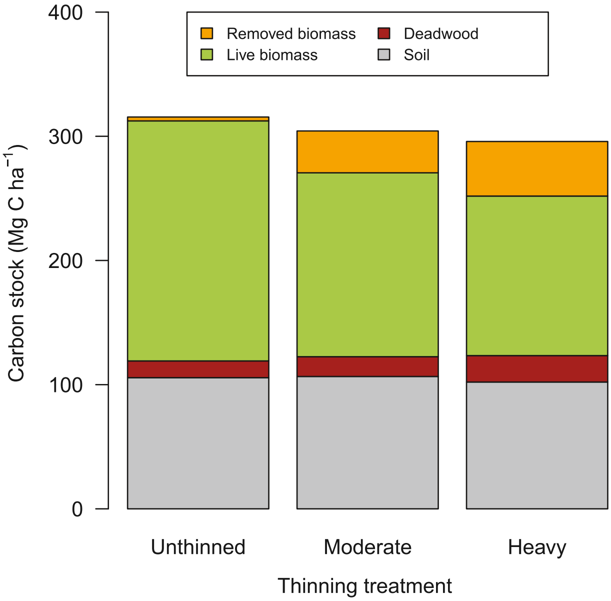

Fig. 1 Total carbon stock distribution by forest components and thinning treatment

Aboveground biomass C stock accounted for 43 % of the total C stock (on-site) in the *U* treatment, 39 % in the *M* treatment and 36 % in the *H* treatment. Belowground biomass C stock comprised 19 %, 16 % and 15 % of the total C stock whereas deadwood made up 4 %, 6 % and 8 % for the *U*, *M* and *H* treatments respectively. The soil C stock amounted to 34 % (28 % mineral soil and 6 % forest floor), 39 % (32 % mineral soil and 7 % forest floor) and 41 % (35 % mineral soil and 6 % forest floor) for the *U*, *M* and *H* treatments respectively.

4 Discussion

The total on-site C stock, considering all the compartments, was significantly higher in unthinned plots than in thinned plots, mainly due to the biomass component (Fig. 1). This coincides with the results of other studies concerned with the long-term effects of different management practices on C stocks, which reported differences in the amounts of C in the live tree biomass component (e.g., Powers et al. 2011; Simon et al. 2012; Ruiz-Peinado et al. 2013).

When the C stock harvested in thinning operations was added to the biomass C stock (on-site and off-site biomass C stock), differences were also found to exist between the unthinned treatment and heavily thinned stands. This loss of biomass production exhibited by heavily thinned stands in relation to the production of unthinned stands has already been reported in several long term thinning trials in Scots pine stands located in different European regions in terms of volume growth (Chroust 1979; Mäkinen and Isomäki 2004; Río et al. 2008). In Spain, Río et al. (2008) identified a critical basal area, according to Assmann (1970), of 83 % of the unthinned stand in the case of natural Scots pine thinning trials, i.e. the percentage of basal area in relation to the basal area in unthinned stands in which 5 % of the volume growth was lost. In our thinning trial the plots had a mean basal area in the last inventory of 74 % for the moderate thinning and 63 % for the heavy thinning treatments in relation to the unthinned plots, with a loss of 6 % and 8 % respectively in total biomass. These values indicate a lower critical figure than that reported by Río et al. (2008), suggesting a better response to thinning in this trial, probably due to the younger age of the stand (Chroust 1979; Kramer and Röös 1989), approximately half the rotation age. Hence, it is important that the trial is maintained for the full duration of the rotation period in order to evaluate the overall effect of thinning on total C stocks. Moreover, the early thinning applied in the trial appears to be more appropriate as a mitigation strategy than late thinning given the better diameter growth response to thinning found in Scots pine at young ages (Peltola et al. 2002; Mäkinen and Isomäki 2004; del Río et al. 2008).

The differences in live tree biomass C stock between treatments are mainly explained by the lower densities and basal areas maintained in thinned stands (Table 1). These lower stocking levels might have consequences in terms of litterfall input (needles, bark, deadwood or rootlets) and therefore, could also affect the amount of forest floor and deadwood components. A reduction in litterfall with thinning intensity was reported in Spain for *Pinus pinaster* (Roig et al. 2005) and *P. sylvestris* (Blanco et al. 2006), although in the case of the former, the effect of thinning on litterfall was found to disappear 5 years after treatment and in the case of the latter, this temporal effect could not be verified due to the short-term nature of the study. In contrast to other studies (e.g., Vesterdal et al. 1995; Jonard et al. 2006) we found no differences in forest floor C stock among the different thinning intensities tested. Litterfall, decomposition ratios and harvesting methods may have a bearing on this finding. In our study, the use of stem-only harvesting allowed logging residue to remain in the stand, hence there was no significant decrease in the C stock of this compartment. However, the *H* treatment exhibited the lowest value (14.7 Mg C ha^{-1}), suggesting a lower litter supply and possibly a greater micro-climatic effect of thinning on decomposition, as reported in other studies (e.g., Vesterdal et al. 1995; Skovsgaard et al. 2006). A probable increment in soil temperature and greater soil water content due to the lower stand density in the heavy thinning treatment might lead to an increase in the decomposition rate and forest floor reduction (Aussenac 1987). However, Blanco et al. (2011) in their Scots pine thinning experiments found differences in needle decomposition rates in thinned stands in comparison to unthinned stands, the rates being higher in unthinned plots, although they did not identify changes in soil temperature and soil moisture.

Neither forest floor bulk density nor mineral soil bulk density increased as a result of compaction during thinning operations (Table 3), as stated in other studies (e.g., Jandl et al. 2007; Schulp et al. 2008). Leaving logging residues on the floor could also help minimize soil compaction, thus helping to maintain soil C stocks (Han et al. 2006; Page-Dumroese et al. 2010). In the thinned stands, the greater bulk densities found in the deepest layer sampled (20–30 cm) (Table 3) may also be associated with the more rapid soil decompaction in upper layers of the mineral soil (Froehlich et al. 1985).

As regards the deadwood component (Table 2), the largest amount of fine woody debris in thinned plots may be associated with the stem-only harvesting method used in the trials. The fine woody debris compartment comprised the greatest percentage of woody debris (more than 90 % in all treatments), while logs and snags made up only a small fraction, even in the unthinned treatment, probably as a consequence of the low mortality rate.

The single largest C pool is the mineral soil, the current global stock amounting to around 383 Pg C, which represents 44 % of the total C stock in world forests (Pan et al. 2011). In this study, the soil C stock accounted for 34 % of the total C stock in the *U* treatment, 39 % in the *M* treatment and 42 % in the *H* treatment. The potential for C sequestration in the soil and consequent contribution to mitigating the effects of climate change is deemed to be high, especially as a result of the afforestation of marginal agricultural land (e.g., Lal 2004b; Jandl et al. 2007). Although the sequestration rate in soils may be lower than in biomass (Jandl et al. 2007), the residence times are longer and the C is often sequestered for centuries.

The soil C stock in the studied Scots pine stand varied from 102 to 107 Mg C ha^{-1}, including forest floor and the upper 30-cm of mineral soil (Table 2). These results are in accordance with those of other studies of this species. In Central Spain, Díaz-Pinés et al. (2011) found between 90 and 140 Mg C ha^{-1} (to a depth of 50-cm) in natural stands and Charro et al. (2010) reported a higher figure of 166 Mg C ha^{-1} (to a depth of 20-cm) in a reforested stand. In Europe, Janssens et al. (1999) reported C stocks of 144 Mg C ha^{-1} in a Belgian plantation of *P. sylvestris* (to a depth of 1-m) and Schulp et al. (2008) reported an amount of 98 Mg C ha^{-1} (to a depth of 20-cm) in a plantation of the same species in the Netherlands.

The C stock contained in the first layer considered in this study (0–10 cm) was as large as the combined stock of the other two layers considered (10–20 cm and 20–30 cm), highlighting the importance of the mineral soil upper layer as a C pool (Table 5). Hence, it is particularly important that disturbances to the upper part of the mineral soil are minimized to avoid C loss. As regards forest management, this may imply the use of more 'friendly' harvesting techniques.

The C stock data for the forest floor and mineral soil suggest that the three, 10-yearly thinning operations performed to date have not had a significant impact on soil C. The same finding was reported in other studies concerning the influence of management systems on C stocks (e.g., Skovsgaard et al. 2006; Chatterjee et al. 2009; Jurgensen et al. 2012) including a recent thinning study conducted in southern-central Spain (Ruiz-Peinado et al. 2013) and focusing on Mediterranean maritime pine (*Pinus pinaster* Ait.). Thinning recommendations for Scots pine in the study area (del Río et al. 2008) advise heavy thinning interventions at early stages, as in our trials, and light thinning in the second half of the rotation, which should reduce the potential impacts of thinning on this compartment.

Given the finding that thinning has no effect on soil C stocks, combined with the fact that the live tree biomass compartment (both above and belowground) contained the largest C stock in the forest (around 62 % for *U*, 55 % for *M* and over 51 % for the *H* treatment) it may be concluded that the live tree biomass along with the biomass removed in the thinning treatments could be used as indicators for monitoring the sustainability of forest management in terms of C sequestration.

As previously mentioned, thinning operations in this Scots pine afforestation involve a small loss of production (total biomass, including also removed biomass) which slightly reduces the mitigation capacity of this kind of afforestation. However, it is important to take into account the C sequestrated in wood products, which depends to some extent on the type of thinning applied. Thinning from below is the most favorable since it concentrates the growth on the largest trees, increasing the amount of merchantable wood (Hoover and Stout 2007).

Most of the pine plantations in Spain were established to provide a protective function; hence, wood production was not the main objective. Today, multi-objective management is considered more appropriate in most of these forests in order to address issues such as soil protection or wildlife habitat creation whilst also taking into consideration the role of forests as C sinks both on-site (biomass and soil) and off-site (wood products or bioenergy). Since large agricultural areas were forested using *Pinus* species and later received little or no silvicultural intervention, many of these pine forests are now highly homogenous in terms of composition, age structure, high densities and continuous extensions of forested surface, requiring the application of thinning treatments to maintain their stability. This study highlights the sustainability of thinning treatments with regard to C stocks since the soil C stock is not affected and the loss in terms of total biomass is small (8 %) during the first half of rotation. Furthermore, the use of harvested wood products from the thinning operations could play a key role as a mitigation strategy, particularly in areas with high fire risk.

5 Conclusions

Scots pine afforestation has proven to be a successful climate change mitigation strategy, as confirmed by the large quantities of C found in this plantation in the middle of the rotation period.

The mitigation capacity of Scots pine stands is slightly modified by thinning, suggesting the long-term sustainability of these interventions in terms of C stocks. Findings with regard to the effects of thinning on C stocks indicated a small loss in total biomass (including both on-site and off-site stock), but only when heavy thinning was applied. Moreover, there was no effect on forest soil (forest floor and mineral soil). Hence, thinning treatments do not disturb the potential high soil C sequestration rates associated with afforestation. Furthermore, the stem-only harvesting method avoids a decrease in the C stock levels of the forest floor.

Acknowledgments We would like to thank to Eduardo López-Senespleda, Gerardo Urchaga and Antonio Urchaga for the field support and the staff of the INIA-CIFOR soil laboratory (Salvador Sastre and Puri Pereira) for their assistance. We also thank to all people who maintained the long term trial of this study. Adam Collins carried out the English revision. This work has been partially funded by the projects AGL2011-29701-C02-00, AT010-007 and AT013-004. We are grateful to the two anonymous reviewers for the suggestions that improved the final version of the manuscript.

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