Forest thinning impact on carbon stock and soil condition in Southern European populations of *P. sylvestris* L.

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Abstract

An important aspect of sustainable forest management is to assess the impact of forest operations on ecosystem services. This work analyzed the long-term effect of two standard thinning regimes on carbon stocks both in tree biomass and soil compartments as well as its effect on soil condition. The target population was a 90-year-old Scots pine (*Pinus sylvestris* L.) stand in southwestern Europe. Soil condition was measured as dry mass of the forest floor and concentration of carbon, nutrients in the forest floor as well as exchangeable cations, effective cation exchange capacity, pH and bulk density in the mineral soil. Repeated thinnings from below in a southern European population of Scots pine led to a reduction in cur‐ rent on-site carbon stock in tree biomass of 28% in moderately thinned stands (D grade: average residual basal area of 65–79% relative to the control plots) which was consistent with an observed loss of volume production. However, the inclusion of the amount of carbon exported off-site with harvested biomass reduced the decrease in stock to 4.8%. Nutrient concentrations in the forest floor increased in moderate thinned stands (P, K, Mg and Mn) or were unchanged (C, N and Fe). The selected thinning regime did not alter mineral soil condition. A decreasing pattern of Ca and Mn stocks with depth was consistent with a high reduction of nutrient concentration of elements and higher bulk density with depth. However K, Mg and Na showed stable stocks across depths because of a much smaller reduction of nutrient concentrations in deeper layers relative to the surface layer. We hypothesized that this stable pattern with soil depth was due to leaching. The sustainability of forest thinning is a trade-off between loss of standing biomass and increasing stand stability as long as other indicators, like soil condition, do not significantly change.

Introduction

Sustainable forest management (SFM) is the paradigm of forest stewardship and is often claimed to be the only option for maintaining ecological integrity and provision of services from forests (Rempel et al., 2004). Aboveground and soil carbon (C) stocks and the changes in soil condition must be accurately assessed to assure the delivery of ecosystem services in forest mitigation strategies.
Soil is one of the most important components of forest ecosystems. It provides nutrients, water

and support for vegetation and makes up a significant C reservoir of terrestrial ecosystems. Forest soil condition usually refers to chemical and physical properties that characterize a site as related to specific objectives like, among others, plant productivity improvement or monitoring changes due to anthropogenic disturbances (i.e. pollutant deposition or harvesting). The term is widely used in Europe as an indicator to evaluate forest ecosystems health and vitality (MCPFE, 2002) and to report current status or changes in forest soils (de Vos and Cools, 2011). The most common soil properties describing the soil condition are bulk density, pH, nutrient budgets, and C and nitrogen (N) stocks.

By far, C is the most studied component of soil condition. The importance of forest soils as C reservoirs is reflected in the fact that about 50% of C in forests is stored in mineral soil and forest floor (Pan et al., 2011). Soil C sequestration is also considered to be a powerful strategy for mitigating climate change (Lal, 2005). European temperate forests were considered to be stable in terms of C sequestration between 1990 and 2007 and the estimated annual change in C stock in litter and soil in European temperate forests accounted for 31% of the total C sink between 2000 and 2007 (Pan et al., 2011). Aboveground C and the changes induced by harvest and tending operations are also considered good indicators of sustainability of forest practices when mitigation of global change is considered (Ruiz-Peinado et al., 2014).

Another important component of soil condition is total soil N stock, which is widely studied (e.g. Chu et al., 2010; DeLuca and Zouhar, 2000; Guan et al., 2015; Hafner and Groffman, 2005; Jonard et al., 2008; Murty et al., 2002). Total N is correlated with available N in the soil solution and it influences soil microbial activity and humus form. In addition, an increasing N stock could determine the sustainability of forest systems as C sink (Rastetter et al., 1997).

Nutrient pools and budget estimations are generally studied in litterfall (Blanco et al., 2005; Parrotta et al., 2009), forest floor (Jonard et al., 2006) and mineral soils (Johnson et al., 2014, 2011; Nobles et al., 2009). Forest soils play a major role in nutrient cycles, providing regulating and supporting services. Forest soil condition depends on the rock parent material, vegetation cover and local climate. Human interventions like harvesting and tending diminishes aboveground cover, and thus C, and might affect forest soil condition. Hence the importance of adequately estimating and monitoring C and nutrient stocks in forest ecosystems and the need to determine the impact of forestry practices on these stocks.

Thinning is a core management practice in forestry. It regulates the distribution of growing space so that standing trees may benefit in terms of competition, growth and health status (Smith et al., 1997). Jandl et al. (2007) reviewed the role of thinning in soil C sequestration and concluded that although stability was guaranteed, the size of the C pool shrank. However, empirical evidence has shown contradictory results. Whereas multiple forest thinning did not alter mineral soil C content in afforestations of *Pinus sylvestris* L. stands and Mediterranean *Pinus pinaster* Ait. (Ruiz-Peinado et al., 2014, 2013) or in *Pinus resinosa* Ait. forests (Jurgensen et al., 2012) it might have reduced N, P, K nutrition by decreasing forest floor mass and extracting nutrients in thinned trees (Jonard et al., 2008), although site and climatic variables also affected forest floor mass in managed forests (Blanco et al., 2006). The study of the impact of silvicultural practices on C stock has been analyzed in the short- and long-term after a final harvest or after several years of repeated intermediate cuttings (i.e. forest thinning). Results in the literature are highly influenced by differences in experimental material and methodology used. Synthesis studies based on meta-analyses have shown that C stored in forest floor is more vulnerable to harvesting method, both thinning and clear-cut, than mineral soil and this effect is mediated by species composition whereas soil taxonomic order is more influential in mineral soil than harvest intensity (Nave et al., 2010). Harvest has been found to affect insignificantly either to mineral soil C storage (Johnson and Curtis, 2001) after clear-cut or forest floor and mineral soil after partial cutting (Zhou et al., 2013) whereas C in aboveground biomass (AGB) decreased after partial cutting (Zhou et al., 2013).

The functional group of species also exerted an important control on the effect of the intensity of management on C storage, from little impact on conifers to decreasing C values in hardwoods (Powers et al., 2011, 2012). Harvesting depleted nutrients in man- aged forests although the impact was dependent on the harvest type used (i.e. whole tree vs. stem only) or if other treatments like burning or residue mastication were also applied (Johnson et al., 2008, 2014). Soil nutrient concentrations is affected by management and species identity (Augusto et al., 2002; Vesterdal et al., 2013). Thinning has also a variable effect on litterfall nutrient concentrations. For example, litterfall P and K is affected by thinning intensity with no clear pattern whereas N is not affected by thinning regime in *Acacia mangium* stands (Kunhamu et al., 2009).

The objective of this study was to assess the long-term effect and sustainability of two standard thinning regimes in a natural Scots pine population located in southern Europe as indicated by C stock and soil condition change. The soil properties measured were dry mass of the forest floor and concentration of C, N, total elements in the forest floor, and exchangeable cations, the cation exchange capacity, pH, and bulk density in the mineral soil. The specific research question to be answered was if repeated forest thinning altered soil condition in Scots pine stands.

Material and methods

Study site and thinning experimental design

The experimental site is located in Covaleda (Soria), Central Spain, in a single-species naturally regenerated stand of *P. sylvestris* L. (41°56′ N; 2°49′ W). The thinning trial was set up using a randomized complete block design with three blocks and three treatments (del Río et al., 2008). The treatments were: Control (A grade; no intervention), light thinning from below (C grade; average residual basal area of 80–90% relative to the control plots) and moderate thinning from below (D grade; average residual basal area of 65–79% relative to the control plots). A total of 9 plots were analyzed. The stand age during the experiment ranged from 50 to 90 years. Stem-only harvesting method was performed 4 times when the stand ages were 50, 55, 65 and 75 years. Logging residues were left on the site. The diameter at breast height of all trees was measured and a subsample of tree heights was recorded. Table 1 shows the main forestry attributes and C stock in aboveground and belowground biomass measured during the last available inventory in 2008 when stand age was 90 years old.

Aboveground and belowground tree biomass

Tree data were converted into biomass using allometric biomass equations (Ruíz-Peinado et al., 2011). These equations are arranged in a compatible system of additive models that estimates biomass from five fractions: stem, thick branches (Ø > 7 cm), medium size branches (2 cm < Ø < 7 cm), twigs and needles, and coarse roots. Woody biomass was converted to C using a conversion factor for the species of 45.9 g C (100 g dry biomass) (Herrero de Aza et al., 2011). Table 1 shows the average aboveground and belowground biomass by treatment. Total or accumulated C, including living and harvested C during thinning operations was also computed.

Soil sampling for C stock and soil condition

In 2010 (with a corresponding stand age of 92 years old), four points were marked at a distance of five meters from the center of each experimental plot in four compass directions (North East, South East, South West and North West). These points were considered the center of four circular subplots (radii 5 m) where a representative 25 x 25 cm area was selected to collect all the forest floor layers using a metallic frame. Forest floor depth was measured by removing the area close to the edge of the frame down to the mineral soil. Three forest floor layer depths were annotated:

Litter(OL), Fragmented (OF) and Humus (OH). The Humus layer was always thinner than 1 cm and was joined to the F layer (OFH). We repeated this sampling approach in each subplot. The final forest floor sampling per layer was composited by plot.

Table 1. Average forestry attributes and stock per area basis by treatment in aboveground and belowground biomass. In parenthesis standard error of the mean.

Treatment	N (stems ha^{-1})	dg (cm)	G (m^2 ha^{-1})	Ho (m)	Wa (Mg ha^{-1})	Wb (Mg ha^{-1})
A	1386 (92)	21.6 (0.7)	50.6 (2.1)	17.0 (0.1)	379.1 (18.9)	83.8 (3.5)
C	858 (41)	24.6 (0.7)	40.6 (0.8)	17.1 (0.7)	307.1 (12.5)	67.3 (1.3)
D	706 (45)	25.5 (0.9)	35.7 (0.4)	17.3 (0.7)	270.2 (10.9)	59.0 (0.6)

Treatments: A control, C low thinning, D moderate thinning, N stock density, dg: quadratic mean diameter, G: basal area, Ho: dominant height, V: stand volume; Wa: aboveground biomass, Wb: belowground biomass. Stand age 90 years-old.

Below the forest floor sampling point a pit of 30 cm depth was dug and mineral soil samples at 0–10 cm, 10–20 cm and 20–30 cm depth were collected. Soil was composited and homogenized within the same plot. A photograph was taken of each pit and analyzed in the laboratory to evaluate 'stoniness' in every soil layer. We assumed that the percentage of stones on the vertical surface of the profile is similar to that of a known volume of soil in the same plot. Images were analyzed with *ImageJ* software (Schneider et al., 2012). This value was then incorporated to calculate C, total N and nutrient stocks. Bulk density of unaltered soil was calculated by extracting a cylinder (10 cm high and 6.5 cm wide) at the same three depths in each plot.

Laboratory analysis and stock calculation

Organic and mineral soil samples were stored in cloth bags in the field. In the laboratory, soil organic C and N concentration (SOC and SON) were calculated via dry combustion using a LECO HCN-600. Soil inorganic C was not detected and SOC values represented total C concentration. Forest floor samples were digested in a high pressure acqua regia system (ETHOS PLUS) and nutrient element concentrations (mg g^{-1}) were measured using ICP-OES (Perkin–Elmer, Optima 2000). Exchangeable cations in mineral soils were calculated using spectrometry in the 0.1 mol l^{-1} barium chloride extract following methods approved by ICP-Forests (Cools and De Vos, 2011) based on methods ISO 11260 and ISO 14254 (ISO, 1994a, b).
Soil bulk density was calculated as the quotient between the mass of the fine fraction in the core segment and volume of the cylinder (Throop et al., 2012). Soil texture was computed according to Sedimentary Method ISO 11277 (ISO, 2009), and textural classes were classified according to the USDA-FAO triangle (FAO, 2006).
C and N stocks of the forest floor in each plot were calculated as the product of element concentration and sample dry mass divided by sampling area. C, N and nutrient stocks in mineral soil were calculated according to Eq. (1)

$$Y_{stock} = Y_{conc} \cdot \rho \cdot \lambda (1 - f) \cdot 10 \qquad (1)$$

where Y_{stock} is C, N and nutrient stock in the mineral soil (Mg ha^{-1}), Y_{conc} is the concentration of the target element in the mineral soil (kg Mg^{-1} soil), q is bulk density (Mg soil m^{-3}), k is the depth of the sampled layer (m), f is the fraction of rock fragments >2 mm in the soil.

Statistical analysis

Current C content in living tree biomass was calculated at the end of the measurement period (stand age of 90 years) and analyzed using a mixed effect modeling approach where treatment

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doi:10.1016/j.foreco.2015.08.005

was considered a fixed effect and block as a random effect. Bulk density, pH, forest floor organic C and total N stocks, as well as forest floor and mineral soil C, N concentration and exchangeable cations were treated as repeated measures in a vertical space (soil layers/depths), treating the correlation within observations with a covariance structure that allows for greater variances from top to bottom. The selected structure was Heterogeneous Toeplitz. The outputs were generated using PROC MIXED of SAS/ETS software (SAS Inc., 1999). A least squares means differences test was per- formed if fixed effects were significant.

Results

Aboveground and belowground tree biomass

There were no differences between moderate and heavy thinned stands for all compartments considered, although biomass fractions showed greater C stock in the control plots, with the exception of medium size branches biomass in light thinning which is not significant different from unthinned plots. However, the inclusion of harvested C in the calculations revealed no differences between unthinned and thinned plots (Table 2).

Table 2. Aboveground and belowground carbon stock (Mg C ha^{-1}) in tree biomass by treatment.

Biomass fraction/treatment	Control	C grade	D grade
Stem biomass	71.47 ± 4.51 [a]	65.79 ± 3.45 [b]	57.88 ± 2.95 [b]
Medium size branches	7.17 ± 0.46 [a]	6.85 ± 0.18 [ab]	6.15 ± 0.16 [b]
Twigs	12.1 ± 0.53 [a]	10.66 ± 0.38 [b]	9.39 ± 0.26 [b]
Roots	38.47 ± 1.98 [a]	34.23 ± 0.80 [b]	30.04 ± 0.37 [b]
Total	129.23 ± 7.36 [a]	105.97 ± 3.66 [b]	93.3 ± 2.80 [b]
Accumulated	148.66 ± 9.36 [a]	142.6 ± 5.67 [a]	141.46 ± 5.80 [a]

Treatments as in Table 1. Results are presented as mean values and standard errors of the mean at significance level of 0.05. Accumulated carbon includes carbon harvested in thinning and natural mortality in control plots. Different letters indicate significant differences in C stocking at $a = 0.05$.

Dry mass in forest floor

Forest floor dry mass decreased in thinned stands from 26.19 ± 8.03 Mg ha^{-1} in control plots to 23.29 ± 8.57 Mg ha^{-1} in light thinning and 17.49 ± 6.45 Mg ha^{-1} in moderate thinning treatments (Appendix A, Fig. A1). However, such differences were not statistically significant (p-value = 0.4366). The accumulation of dry mass is higher in OFH layers than in the OL layer, leading to significant differences between forest floor layers (p- value = 0.0036). The interaction between treatment and layer was statistically insignificant (p-value = 0.7106).

C, N and nutrient concentrations and stocks in the forest floor

Forest floor nutrient and C and N concentrations are shown in Table 3. All concentrations increased from OL to OFH horizon with the exception of C and Ca. Thinning intensity had no effect on C, N, and Fe concentrations (mg g^{-1}) in forest floor. The concentration of P, K, Mg and Mn (mg g^{-1}) was higher in moderate thinned plots (grade D) than in control plots (grade A). No differences were detected between light and moderate thinning or moderate and control plots for these elements (Appendix B, Table B1). The most erratic pattern was found in Ca, with differences between control and light thinning and light thinning and moderate thinning. However, Ca concentration in the forest floor of unthinned plots was similar to that found in moderate thinned ones (Appendix B, Table B1). For all elements, the interaction between organic layer and treatment was not significant.
Nutrient stocks in the OL layer did not differ between treatments whereas forest floor stocks of C, N and Ca were significantly lower in moderate thinned plots in the OFH layer (Figs. 1a, b, and

2c). Stocks of P, K, Mg, Mn and Fe were not different between treatments (Fig. 2).

Table 3. Soil data description by treatment and soil layer for forest floor.

Thinning grade	Layer	Carbon and nitrogen concentration		Nutrient concentration (mg g^{-1})						
		C (mg g^{-1})	N (mg g^{-1})	Ca	Mg	K	P	Mn	Fe	Zn
A	OL	538.1 (5.7)	0.6 (0.03)	3.71 (1.5)	0.33 (0.1)	0.44 (0.1)	0.25 (0.14)	0.61 (0.4)	0.23 (0.06)	0.02 (0.004)
	OF + OH	377.8 (49.3)	0.9 (0.1)	3.27 (0.3)	0.62 (0.2)	1.41 (0.4)	0.53 (0.08)	1.08 (0.5)	4.42 (2.50)	0.04 (0.02)
C	OL	541.7 (6.2)	0.5 (0.08)	4.99 (0.11)	0.42 (0.02)	0.68 (0.1)	0.35 (0.06)	0.99 (0.1)	0.28 (0.12)	0.03 (0.003)
	OF + OH	383.9 (39.9)	0.9 (0.03)	4.05 (0.55)	0.65 (0.03)	1.49 (0.2)	0.58 (0.26)	1.48 (0.5)	4.08 (0.38)	0.05 (0.01)
D	OL	539.3 (4.5)	0.6 (0.06)	6.64 (0.7)	0.63 (0.07)	1.39 (0.01)	0.56 (0.02)	1.39 (0.3)	0.24 (0.01)	0.052 (0.02)
	OF + OH	404.4 (105.2)	0.9 (0.23)	3.74 (1.2)	0.66 (0.12)	1.53 (0.5)	0.61 (0.17)	1.51 (0.7)	6.57 (4.7)	0.041 (0.01)

Thinning grades as explained in Table 1 and material and methods. In parenthesis standard deviation of the mean.

Bulk density and pH in mineral soil

Mean values for bulk density and soil pH by treatment are shown in Table 4. Bulk density, and soil pH increased from the top- soil to the 30 cm. Soil pH ranges from 4.5 to 5.0 (pH H$_2$O) and 3.6 to 3.9 (pH KCl). Soil bulk density increased from the topmost layer to the deepest layer, showing differences among layers. Thinning intensity did not affect either pH or bulk density values (Appendix B, Table B2).

C, N and nutrient concentrations and stocks in mineral soil

Nutrient and C and N concentrations decreased with depth (Table 3). Thinning intensity had no effect on the concentration of any of the variables tested in the mineral soil. All predictors showed a decreasing level of concentration from the first 10 cm of mineral soil to 20 cm and to 30 cm (Table 3). The least squares means test indicated that there were no differences in N concentration between 10–20 cm and 20–30 cm (p-value = 0.3193) whereas K$^+$ showed no concentration differences in the first 20 cm. Mg^{2+} concentration differed only slightly between 0– 10 cm and 20–30 cm (p-value = 0.0428). For the rest of the depths and predictors differences were statistically significant (Appendix B, Table B3).

Thinning intensity did not influence C and N stocks in the mineral soil and differences were only found due to soil depth (Fig. 3), Treatments A and C generated similar C stocks (122.9 and 112.2 Mg ha—1, respectively) whereas treatment D had the highest C stock over the whole profile (135.7 Mg ha—1). In the case of thinned plots, 49% of C was stored in the first 10 cm of the total C in the mineral soil to a depth of 30 cm, whereas for 20 cm the percentage increased up to 79%. Control plots stored 56% and 85% in the first 10 and 20 cm respectively.

Stocks of Na, Mn and K were not affected by neither depth nor thinning whereas higher values of Ca and Mg stocks were found in 10–20 and 20–30 cm. On the top soil, Ca and Mg stocks were similar among treatments (Fig. 4b and c).

Table 4. Soil data description by treatment and soil depth for mineral soil.

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Thinning grade	Depth (cm)	Soil reaction		Soil physical properties				Carbon and nitrogen soil concentration			Soil exchangeable cations (cmol$_c$ kg^{-1})						
		pH$_{H2O}$	pH$_{KCl}$	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	C (mg g^{-1})	N (mg g^{-1})	C:N	Ca^{2+}	Mg^{2+}	K$^+$	Na$^+$	Mn^{2+}	H$^+$+Al^{3+}	CEC
A	0–10	4.5 (0.1)	3.6 (0.1)	1.11 (0.07)	66.6 (4.0)	20.5 (2.3)	13.5 (2.2)	61.6 (12.9)	2.4 (0.5)	25.6 (0.6)	1.46 (0.7)	0.24 (0.06)	0.24 (0.05)	0.03 (0.01)	0.95 (0.33)	2.35 (0.32)	5.27 (0.96)
	10–20	4.9 (0.03)	3.9 (0.00)	1.25 (0.05)	68.1 (5.0)	19.5 (4.0)	12.4 (1.0)	28.9 (5.0)	0.9 (0.1)	32.7 (3.2)	0.65 (0.2)	0.17 (0.07)	0.19 (0.06)	0.03 (0.01)	0.39 (0.12)	1.51 (0.20)	2.93 (0.63)
	20–30	4.8 (0.1)	3.9 (0.1)	1.43 (0.05)	64.2 (6.6)	21.4 (4.5)	14.4 (2.2)	12.4 (5.0)	1.0 (0.5)	16.4 (9.3)	0.45 (0.2)	0.14 (0.08)	0.16 (0.06)	0.02 (0.06)	0.21 (0.06)	0.91 (0.21)	1.88 (0.51)
C	0–10	4.6 (0.1)	3.6 (0.1)	1.00 (0.07)	67.3 (0.3)	20.4 (0.4)	12.4 (0.5)	55.6 (6.7)	2.1 (0.2)	26.8 (1.7)	1.05 (0.4)	0.18 (0.05)	0.19 (0.04)	0.72 (0.19)	0.72 (0.19)	2.78 (0.41)	4.94 (0.95)
	10–20	4.9 (0.1)	3.8 (0.1)	1.26 (0.49)	66.3 (2.5)	20.4 (0.8)	13.3 (1.7)	27.1 (15.4)	1.0 (0.1)	26.8 (0.8)	0.60 (0.2)	0.14 (0.03)	0.16 (0.03)	0.36 (0.07)	0.36 (0.07)	1.66 (0.18)	2.94 (0.23)
	20–30	5.0 (0.1)	3.9 (0.1)	1.47 (0.09)	64.5 (3.3)	20.7 (1.4)	14.81 (0.5)	15.4 (0.5)	0.8 (0.2)	20.8 (3.7)	0.39 (0.2)	0.11 (0.04)	0.12 (0.03)	0.19 (0.04)	0.19 (0.04)	1.07 (0.17)	1.89 (0.41)
D	0–10	4.7 (0.2)	3.6 (0.1)	1.08 (0.14)	64.8 (1.6)	20.4 (0.8)	14.8 (2.3)	61.9 (9.5)	2.3 (0.5)	27.5 (2.1)	1.49 (0.3)	0.26 (0.06)	0.23 (0.05)	0.03 (0.01)	0.88 (0.40)	2.61 (0.48)	5.48 (0.92)
	10–20	4.8 (0.2)	3.8 (0.1)	1.28 (0.09)	64.7 (2.2)	20.5 (2.1)	14.8 (1.9)	31.4 (7.9)	1.2 (0.4)	27.6 (5.5)	0.82 (0.2)	0.21 (0.01)	0.20 (0.10)	0.03 (0.01)	0.35 (0.17)	1.45 (0.49)	3.05 (0.58)
	20–30	4.7 (0.4)	3.7 (0.3)	1.53 (0.10)	63.1 (1.5)	20.6 (3.3)	16.3 (0.8)	19.1 (7.2)	0.8 (0.3)	23.4 (2.6)	0.55 (0.1)	0.18 (0.02)	0.18 (0.06)	0.02 (0.01)	0.24 (0.08)	1.11 (0.32)	2.29 (0.30)

Thinning grade as explained in Table 1 and Section 2. In parenthesis standard deviation of the mean. pH calculated with aqueous solution (pH H20) and with potassium chloride (pH KCl). CEC stands for Cation Exchange Capacity, calculated here according to Jonard et al. (2008).

Discussion

The impact of human activities on forest soil C storage and chemical properties have been widely studied in relation to forest fire impact (Granged et al., 2011; Rodríguez-Alleres et al., 2012), conversion of monocultures to more complex ecosystems (Galka et al., 2014), land use change (Kasel and Bennett, 2007; Poeplau and Don, 2013), or harvest intensity (Nave et al., 2010).

In this work we have analyzed experimental data to disentangle the way in which forest thinning in a Scots pine stand in the Mediterranean basin may affect AGB, C and total N stock, and soil condition (bulk density, dry mass, pH and soil nutrient content). The results revealed that biomass and C stock in AGB and forest floor nutrient concentrations significantly changed with thinning intensity. The reduction in AGB in thinned stands represented a reduction of 28% of on-site C (thinning grade D). This reduction is similar to that found in Norway spruce (Nilsen and Strand, 2008) but it is slightly less than in other studies conducted in southwestern Europe. Ruiz-Peinado et al. (2013, 2014) reported 32% and 33% of on-site C loss for *P. pinaster* Ait. and *P. sylvestris* L. afforestations respectively. Our population is 90 years old, whereas those analyzed in Ruiz-Peinado et al. (2013, 2014) are 59 and 52 years old respectively. This age difference may reflect that in the long-term negative thinning effects could have been dissipated.

In addition, the inclusion in stock calculations of harvested biomass (off-site C) reduces the loss of C stock to a negligible 4.8% which is, nonetheless, related to a loss in total volume production reported for thinned stands of this species of 18% (del Río et al., 2008). A slightly higher C loss rate (8%) including harvested C was found in a Scots pine afforestation (Ruiz-Peinado et al., 2014).

Nutrient content decrease may be related to a reduction in forest floor dry mass with thinning intensity (Jonard et al., 2008), which is confirmed by a significant reduction in twig biomass in this study (31%, Table 4) because of a reduction in litterfall production in thinned stands (Blanco et al., 2006; Roig et al., 2005). The dry mass of forest floor is higher in control and light thinned plots whereas the nutrient concentration increased in thinned plots following the dilution effect described by Kunhamu et al. (2009): the higher the litterfall production the lower the nutrient concentration in litterfall and vice versa. This effect is particularly significant in P, K, Mg and Mn in moderate thinned plots (Table 4). Slodicak et al. (2005) reported a decrease in forest floor thickness with thinning whereas only phosphorus stock decreased in thinned stands of Norway spruce. The observational long-term trend in forest

floor is a decreasing nutrient content with thinning. However, experimental evidence has also showed that the thinning regimes proposed in the literature are more site and species sensitive, for example by significantly reducing nutrient stocking in Norway spruce (Jonard et al., 2008) or insignificantly in Scots pine (Novak et al., 2011 and this study). However, a thorough study about the impact of forestry on soil nutrient stock is needed to generalize these results as it has been found for carbon stock in forest floor, which is mediated by species identity and site conditions (Clarke et al., 2015; Vesterdal et al., 2013).

Multiple thinning may alter physical soil conditions because of repeated machinery entrance to forest. Soil compaction is induced on every intervention and it can lead to a reduction in forest productivity (Cambi et al., 2015). Bulk density is an estimator of soil compaction and it is commonly hypothesized that bulk density increases with increased cutting intensity (Tarpey et al., 2008). In our study the bulk density did not change among treatments and only soil depth significantly increased soil compaction (Table 4 and Appendix B, Table B2). Landsberg et al. (2003) found that soil compaction is more common in skid trials than in surrounding areas and Tarpey et al. (2008) suggested that surface soil is not compacted after repeated thinning because of the protection of slash from thinned trees. We hypothesized that this protective effect has also occurred in the studied stand where logging residues were left on the plot.

The depth at which soil samples are taken is also an important factor in the vertical distribution of C stocks and nutrients. In this study we have used 0.3 m as a nominal sampling depth and although this depth may not capture important C reservoirs in dee- per mineral soil (Powers et al., 2012), we found a notable decline in C stock with depth, which is in accordance with studies in other natural pine stands (Conkling et al., 2002). This decline in C stock is more pronounced in unthinned stands, where 56% and 85% of the total C stored in the mineral soil to a depth of 0.3 m, accumulates in the first 0.1 and 0.2 m respectively. In thinned stands this reduction is lower than in control plots. The reason could be the lower litterfall input in thinned stands and the higher decomposition rates due to increasing light transmittance (Augusto et al., 2002) and C accumulation in deeper soil through leaching. However, in Mediterranean climate, where temperature is not a limiting factor but the lack of humidity, the decomposition rates have been found higher in unthinned stands (Blanco et al., 2011). A closer look at key processes is needed to better explain carbon dynamics (Clarke et al., 2015).

The concentration of exchangeable cations in the mineral soil is not affected by thinning grade with higher values in the upper layers for all elements (Appendix B, Table B3). Results also showed a marked decreasing trend with depth in Ca and Mn stocks for all treatments and to a lesser extent for Mg in control and light thinned plots. Although bulk density is not significantly affected by thinning grade a higher bulk density in deeper layers is found. Using data from Table 2 and combining thinning grades, the aver- age increasing bulk density in 10–20 cm relative to the surface layer (0–10 cm) is 18.4% whereas in the deeper layer the bulk density is 39.2% higher than in the surface layer. K nutrient concentration decreases 16.5% and 30.6% from 10–20 cm and 20–30 cm layers relative to the surface layer respectively whereas for Ca the reduction is 47.8% and 65.0%. These values indicate that some leaching may be occurring for K, Mg, Na from surface to 30 cm depth, although a soil solution study should be performed to sup- port or rebate this assumption. With this regard we hypothesize that the non-significant effect of thinning grade indicates that other causes than management are provoking such leaching.

Wall (2012) identified soil pH, P, K, Ca and Mg as soil indicators of harvesting impact on site productivity and forest sustainability. The risk, measured as the probability and the magnitude of a negative outcome following whole tree harvesting as compared to stem only harvesting, was low after thinning operations and disregarded extra mitigation measures in thinned stands. In our study, soil pH was not affected by thinning and concentrations of P, K, Ca and Mg in the forest floor increased with increasing thinning grade. No treatment effect

was identified in mineral soil, indicating that the thinning regime tested can be considered sustainable in terms of soil condition change. Tree-based indicators of sustain- ability like diameter and stand volume after disturbance were also used by Wall (2012) to analyze risks associated to harvesting methods. With this regard, our analysis has shown that standing biomass and carbon are significantly reduced with thinning intensity. When sustainability of forest operations is based on tree or stand attributes it must be taken into account that forest thinning increases stability and maintains the C storage capacity of forests avoiding the risk of higher C losses due to natural disturbances (Jandl et al., 2007).

The use of a single sustainability indicator, either tree- or soil- based, may partially reflect the impact of thinning in the system and highlight that the potential soil nutrient reduction after thinning and its effect on tree growth is not straightforward. In addition, the site dependency of the effect of forest operations in the sustainability of Scots pine forests is a major factor to take into account when studying the impact of forest thinning (Blanco et al., 2005).

We have conducted our study in a single experiment and results are valid for similar environmental conditions and thinning regimes, however a comprehensive study of thinning impact in tree and stand growth and soil conditions would require several thinning trials across environmental gradients (Clarke et al., 2015), with comparable thinning intensities and harvesting methods to address the sustainability of thinning as an adaptive option to mitigate climate change effects (Jandl et al., 2015).

Conclusions

Repeated thinning from below in a Southern European population of Scots pine (*P. sylvestris* L.) leads to a significant stand bio- mass and C stock reduction (on-site C) of 28% in moderately thinned stands (D grade: average residual basal area of 65–79% of that in the control plots). The inclusion of harvested C (off-site C) reduces this decrease in stock to a negligible 4.8%. Although forest floor dry mass is reduced in thinned stands the differences are not significant. P, K, Mg and Mn concentrations in forest floor were significantly higher in moderate thinned stands whereas stocks did not vary across treatments. On the other hand C, N and Fe concentrations were not affected by thinning in the forest floor although stocks were lower in thinned stands due to less forest floor mass. The thinning regime selected did not alter pH, bulk density, C, N and nutrient concentrations and stocks in mineral soil. A decreasing pattern of nutrient stocks with depth is consistent with a high reduction of nutrient concentration of elements and higher bulk density with depth. However K, Mg and Na showed stable stocks across depths because of a smaller reduction of nutrient concentration in deeper layers relative to the surface layer possibly due to leaching, although a deeper study of the soil solution is recommended to support this hypothesis. This study provides experimental evidence of the long term effect of thinning on the C stock and soil condition of southern European populations of *P. sylvestris* L. that will help managers to make decisions when C management and maintenance of the soil condition is included in forestry objectives.

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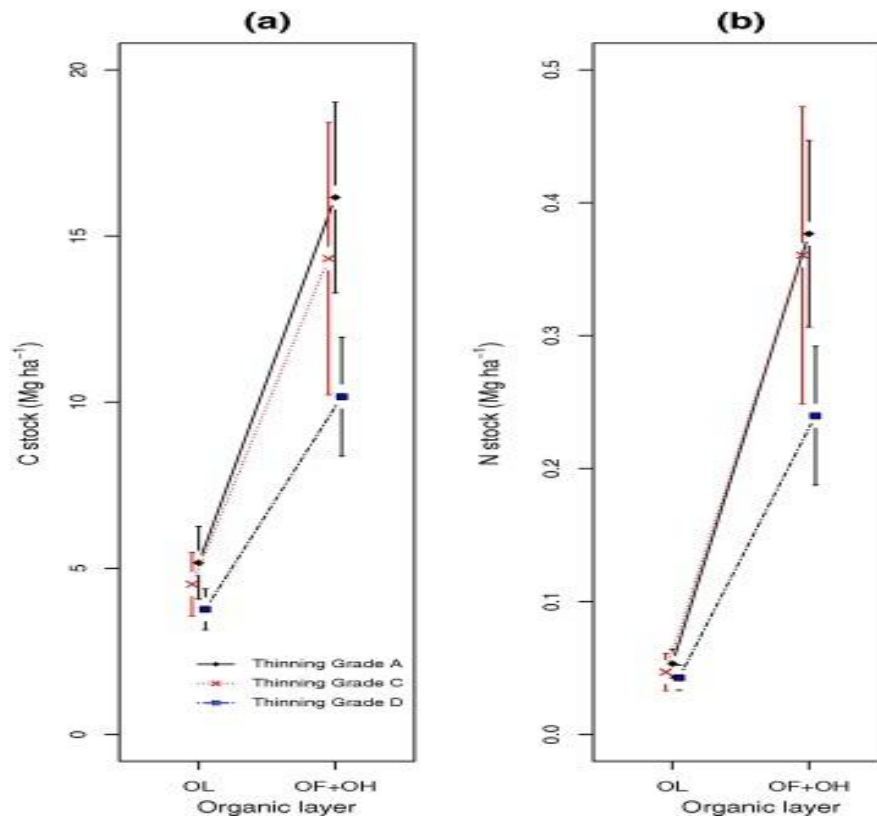
Fig. 1. <u>Organic carbon</u> and total N stock in forest floor across treatment.
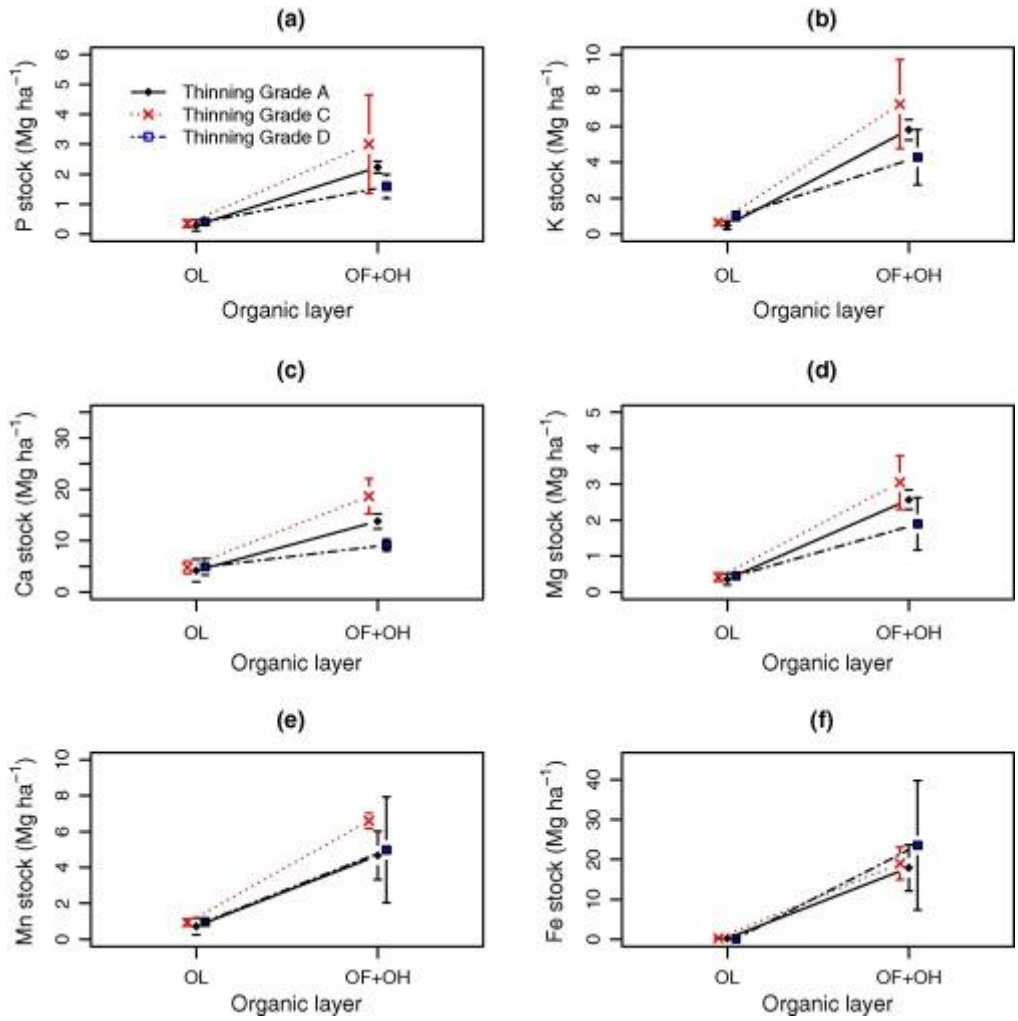
Fig. 2. Stocks (Mg ha^{-1}) of (a) phosphorus, (b) potassium, (c) calcium, (d) magnesium, (e) manganese, and (f) iron in forest floor.

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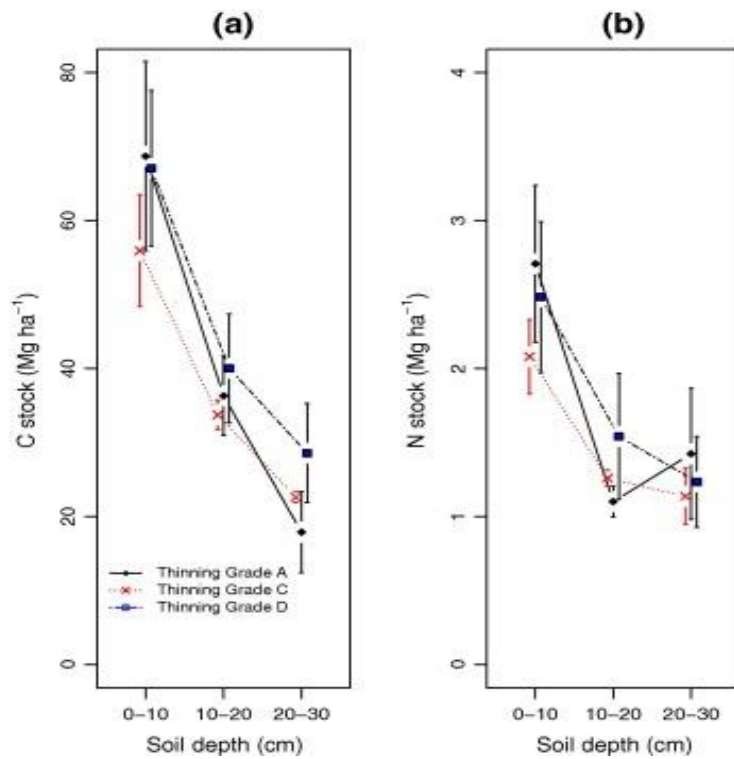
Fig. 3. <u>Organic carbon</u> and total N stock in mineral soil across treatment.

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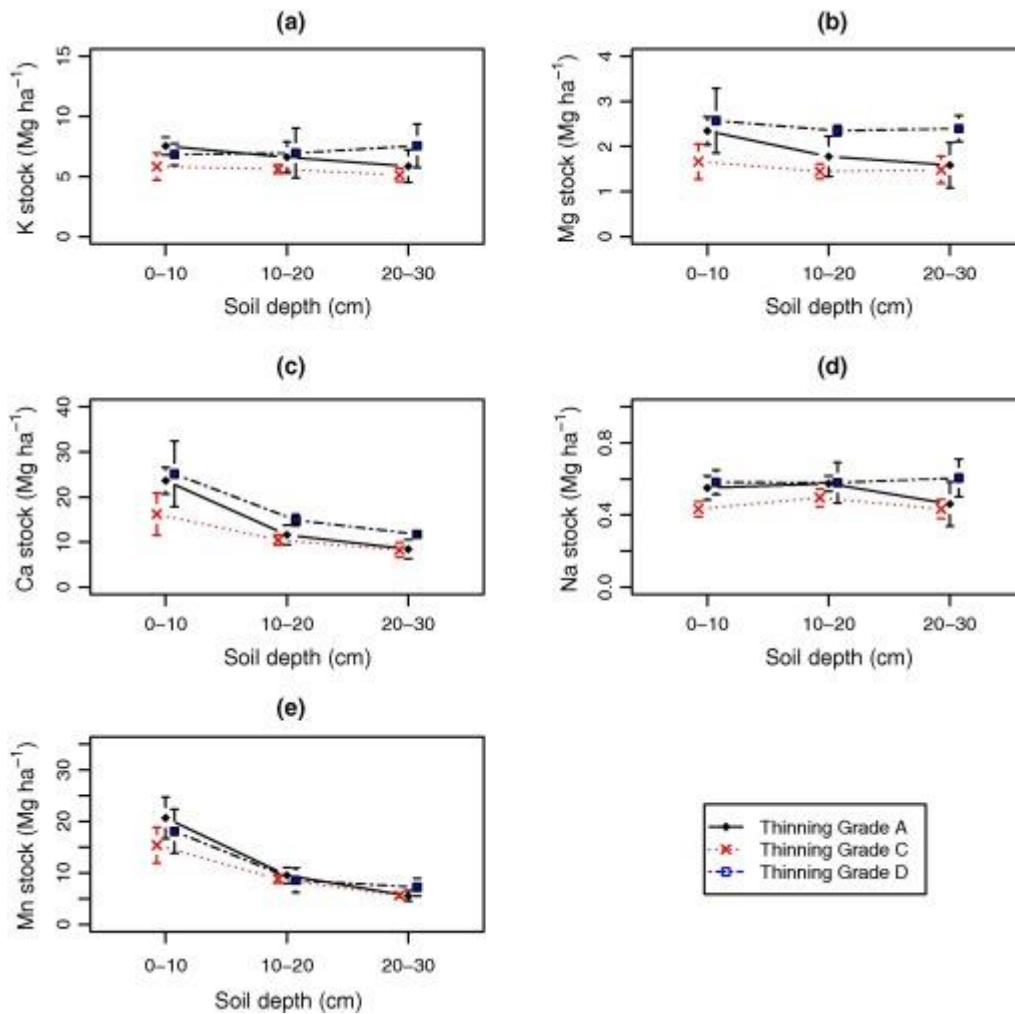
Fig. 4. Stocks (Mg ha^{-1}) of <u>exchangeable cations</u> in mineral soil across soil depth (cm) and thinning intensity.
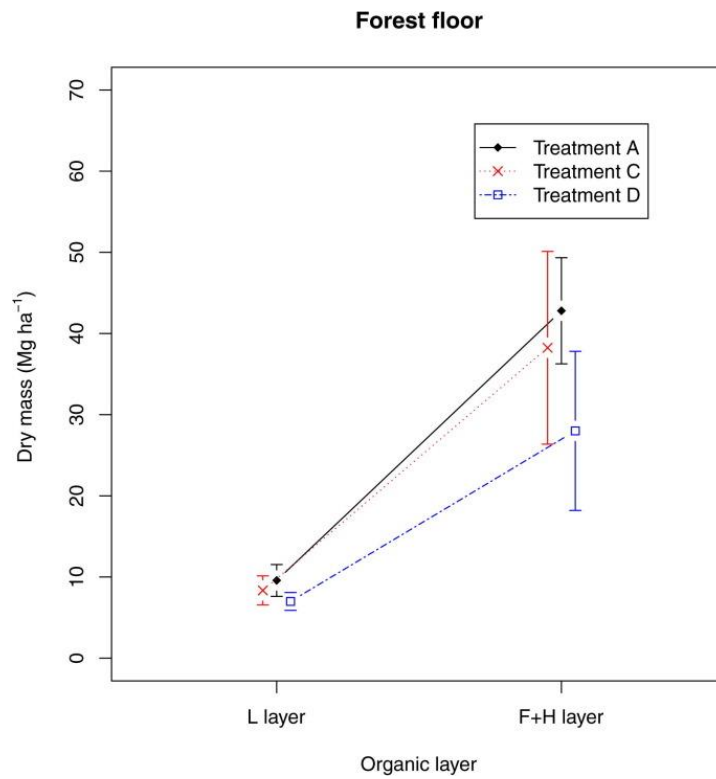
Supplementary Fig. A1. Dry mass in forest floor by layer and thinning intensity.

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Appendix B. Supplementary tables to **Forest thinning impact on carbon stock and soil condition in Southern European populations of *P. sylvestris* L.**

Table B1. Pairwise difference least mean comparison of concentrations by treatment and thinning intensity in forest floor

Element	Fixed Effect Comparison	Estimate	t-value	p > |t|
C	QL-QFH	-150.98 (22.00)	-7.55	< 0.0001
	Thinning Grade A - Thinning Grade C	n.s.		
	Thinning Grade A - Thinning Grade D	n.s.		
	Thinning Grade C - Thinning Grade D	n.s.		
N	QL-QFH	0.35 (0.04)	8.14	<0.0001
	Thinning Grade A - Thinning Grade C	n.s.		
	Thinning Grade A - Thinning Grade D	n.s.		
	Thinning Grade C - Thinning Grade D	n.s.		
P	QL-QFH	n.s.		
	Thinning Grade A - Thinning Grade C	-0.0432 (0.08)	-0.58	0.8376
	Thinning Grade A - Thinning Grade D	-0.2310 (0.07)	-3.38	0.0344
	Thinning Grade C - Thinning Grade D	-0.1882 (0.08)	-2.51	0.1007
K	QL-QFH	-0.6447 (0.14)	-4.65	0.0432
	Thinning Grade A - Thinning Grade C	-0.1686 (0.18)	-0.94	0.6392
	Thinning Grade A - Thinning Grade D	-0.5322 (0.16)	-3.26	0.0394
	Thinning Grade C - Thinning Grade D	-0.3636 (0.18)	-2.02	0.1882
Ca	QL-QFH	n.s.		
	Thinning Grade A - Thinning Grade C	-0.9064 (0.14)	-6.57	0.0015
	Thinning Grade A - Thinning Grade D	-0.2990 (0.11)	-2.64	0.0857
	Thinning Grade C - Thinning Grade D	0.6074 (0.14)	4.40	0.0108
Mg	QL-QFH	n.s.		
	Thinning Grade A - Thinning Grade C	-0.0441 (0.04)	-1.21	0.491
	Thinning Grade A - Thinning Grade D	-0.1503 (0.03)	-4.88	0.007
	Thinning Grade C - Thinning Grade D	-0.1062 (0.04)	-2.91	0.061
Mn	QL-QFH	n.s.		
	Thinning Grade A - Thinning Grade C	-0.3595 (0.19)	-1.94	0.2079
	Thinning Grade A - Thinning Grade D	-0.5716 (0.17)	-3.36	0.0349
	Thinning Grade C - Thinning Grade D	-0.2121 (0.19)	-1.14	0.5244
Fe	QL-QFH	-4.9284 (1.10)	-4.50	0.0108
	Thinning Grade A - Thinning Grade C	n.s.		
	Thinning Grade A - Thinning Grade D	n.s.		
	Thinning Grade C - Thinning Grade D	n.s.		

Thinning grades: A control, C low thinning, D moderate thinning

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Table B2. Pairwise difference least mean comparison by treatment and thinning intensity of pH and bulk density in mineral soil.

Soil condition	Fixed Effect Comparison	Estimate	t-value	p > |t|
pH H2O	0-10 cm - 10-20 cm	-0.251 (0.041)	-6.08	0.0022
	0-10 cm - 20-30 cm	-0.319 (0.056)	-5.65	0.0032
	10-20 cm - 20-30 cm	-0.068 (0.027)	-2.54	0.0974
	Thinning Grade A - Thinning Grade C	-0.071 (0.111)	-0.64	0.8054
	Thinning Grade A - Thinning Grade D	-0.077 (0.111)	-0.69	0.7777
	Thinning Grade C - Thinning Grade D	-0.006 (0.111)	-0.05	0.9985
pH ClK	0-10 cm - 10-20 cm	-0.214 (0.026)	-8.18	<0.0001
	0-10 cm - 20-30 cm	-0.303 (0.065)	-4.64	0.0019
	10-20 cm - 20-30 cm	-0.088 (0.047)	-1.87	0.1929
	Thinning Grade A - Thinning Grade C	0.059 (0.085)	0.7	0.7737
	Thinning Grade A - Thinning Grade D	0.062 (0.085)	0.73	0.758
	Thinning Grade C - Thinning Grade D	0.002 (0.085)	0.03	0.9995
Bulk density	0-10 cm - 10-20 cm	-0.200 (0.038)	-5.23	0.0006
	0-10 cm - 20-30 cm	-0.413 (0.039)	-10.50	<0.0001
	10-20 cm - 20-30 cm	-0.213 (0.033)	-6.40	<0.0001
	Thinning Grade A - Thinning Grade C	0.018 (0.069)	0.25	0.9652
	Thinning Grade A - Thinning Grade D	-0.034 (0.069)	-0.49	0.8775
	Thinning Grade C - Thinning Grade D	-0.052 (0.069	-0.75	0.7466

Table B3. Pairwise difference least mean comparison by soil depth of nutrients concentration in

mineral soil.

Soil condition	Fixed Effect Comparison	Estimate	t-value	p > |t|
C	0-10 cm - 10-20 cm	3.0566 (0.2055)	17.87	<.0001
	0-10 cm - 20-30 cm	4.4096 (0.2955)	14.92	<.0001
	10-20 cm - 20-30 cm	1.3530 (0.1305)	10.37	<.0001
N	0-10 cm - 10-20 cm	1.2288 (0.1222)	10.06	<.0001
	0-10 cm - 20-30 cm	1.3928 (0.1852)	7.52	<.0001
	10-20 cm - 20-30 cm	0.1640 (0.1083)	1.51	0.3193
Ca^{2+}	0-10 cm - 10-20 cm	0.6467 (0.1380)	4.69	0.0014
	0-10 cm - 20-30 cm	0.8744 (0.1533)	5.7	0.0003
	10-20 cm - 20-30 cm	0.2278 (0.0651)	3.5	0.0113
Mg^{2+}	0-10 cm - 10-20 cm	0.0544 (0.0210)	2.59	0.0571
	0-10 cm - 20-30 cm	0.0800 (0.0290)	2.76	0.0428
	10-20 cm - 20-30 cm	0.02556 (0.0145)	1.75	0.226
K^+	0-10 cm - 10-20 cm	0.0356 (0.0215)	1.66	0.1406
	0-10 cm - 20-30 cm	0.0678 (0.0162)	4.18	0.0058
	10-20 cm - 20-30 cm	0.0322 (0.0103)	3.13	0.0204
Na^+	0-10 cm - 10-20 cm	0.0056 (0.0019)	3	0.0112
	0-10 cm - 20-30 cm	0.0111 (0.0022)	5.08	0.0003
	10-20 cm - 20-30 cm	0.0056 (0.0012)	3.31	0.0062
Mn^{2+}	0-10 cm - 10-20 cm	0.4789 (0.0963)	4.97	0.0003
	0-10 cm - 20-30 cm	0.6333 (0.1246)	5.08	0.0003
	10-20 cm - 20-30 cm	0.1544 (0.0313)	4.93	0.0003
$H^+ + Al^{3+}$	0-10 cm - 10-20 cm	1.0833 (0.0812)	13.25	<.0001
	0-10 cm - 20-30 cm	1.5911 (0.1245)	12.78	<.0001
	10-20 cm - 20-30 cm	0.5078 (0.0829)	6.12	0.009
CEC	0-10 cm - 10-20 cm	2.2578 (0.2288)	9.8	<.0001
	0-10 cm - 20-30 cm	3.2111 (0.2910)	11.03	<.0001
	10-20 cm - 20-30 cm	0.9533 (0.1160)	8.22	<.0001

CEC: Cationic Exchange Capacity

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