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ORIGINAL PAPER

Effects of different thinning intensities on soil carbon storage in *Pinus laricio* forest of Apennine South Italy

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Abstract

This study investigated, in a *Pinus laricio* forest of south Italy, how systematic thinning of different intensities (intense thinning, T45; moderate thinning, T25; clear cut, CC; and no thinning, T0) affected soil biological properties, organic matter trend and carbon (C) storage in soil and plants. Soil carbon content and carbon/nitrogen (C/N) ratio were significantly higher in the T45 than in control, T25 and CC. Under T45, the soils had also the highest enzymatic activities, microbial biomass carbon (MBC) and colonies of fungi and bacteria. The humification parameters (humification ratio, HR; the degree of humification, DH; humification index, HI) indicated T45 as the best silvicultural practice-approach method to manage *Pinus laricio* forest for increasing soil carbon storage. The dendrometric parameters evidenced that T45 caused the greatest increment in wood growth (diameter and height), showing that the positive effect of the intense systematic thinning (T45) on the mechanical stability of plantation was related to the ability of trees to accumulate large amounts of carbon in their wood tissues. These data were confirmed by wood density value that was the highest in pine trees under the T45. This study showed that in *Pinus laricio* forest under T45 C stock increased in soil and plant, already 4 years after thinning.

Keywords Pine forest · Carbon storage · Clear cut · Dendrometric parameters · Thinning intensity · Soil biological activity

Introduction

Global warming and climate change concerns have heightened the interest in terrestrial carbon sequestration, in order to explore opportunities for climate change mitigation (Whorf and Keeling 1998; Leung et al. 2014). Forests play a prominent role in the global carbon cycle, contributing to store more than 80% of terrestrial aboveground and 40% of terrestrial belowground carbon storage (Kirschbaum 1996; Six et al. 2002; Alemu 2014). The possible rapid change in the status of forests—from a steady state of minimal CO_2 emission/sequestration to major CO_2 emitter—may offer a cautionary tale of how quickly the source/sink status of large-scale forest C stocks can change (Birdsey et al. 2006). Our understanding of how forest management influences standing C stocks, however, is limited because many of forest carbon studies were focused on quantifying trends in forests in the natural state (Gough et al. 2008; Krug et al. 2012). In unmanaged forests, total ecosystem C stocks generally increase with stand age as pools of living biomass, forest floor material (organic soil horizons) and mineral soil C accumulate through stand development before ultimately leveling off in older stands (Pregitzer and Euskirchen 2004; Bradford et al. 2009). Forest management activities have a number of potential influences on these general trends in C stock dynamics (Johnson 1992; Muscolo et al. 2007a, b; Kim et al. 2009; Muscolo et al. 2010, 2017).

Among silvicultural practices, thinning, which removes some trees from a forest in order to redistribute tree growth onto fewer and consequently with more valuable stems, is a crucial practice in the forest ecosystem management (Weiskittel et al. 2011). It is generally used for a variety of purposes, across both public and private ownerships in many types of forests and regions, representing the physiological basis for tree productivity and a key driver of ecosystem productivity (Chapin et al. 2011). Thinning has significant

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influence on forest soil (affecting root density, microbial communities, organic matter turnover and nutrient budgets), on tree growth and even on the whole forest ecosystem (Tian et al. 2010; Qiu et al. 2011). The decreased density in and below forest canopies, generated by thinning, leads to improved light intensity conditions in forest stands, which in turn speed up litter decomposition rate (Zhao et al. 2014). Thinning is expected to change soil environments, the allocation of aboveground and belowground productivity, root density and turnover (Keith et al. 1997; Bowden et al. 2004). Thus, thinned forests might be expected to have lower rates of C accumulation than unmanaged forests. Increases in soil temperature and moisture following thinning are correlated with increased heterotrophic respiration rates, but reduced live root biomass leads to lower autotrophic respiration rates (Ryu et al. 2009). Thus, total soil CO_2 efflux may be higher (Selig et al. 2008) or lower (Sullivan et al. 2008) in thinned stands than unmanaged stands when comparing the same environmental conditions. In practice, these opposing factors can contribute to either increase in soil C following thinning (Selig et al. 2008) or have little impact on soil C (North et al. 2009). Direct removal of live tree biomass during harvesting generally reduces total ecosystem C stocks (North et al. 2009; Davis et al. 2009) and affects soil microclimate (Jassal et al. 2007). Findings of Achat et al. (2015) clearly demonstrated that using the intensive harvest strategy at its maximum level decreased soil carbon storage. Besides SOC losses, the removal of logging residues had other negative effects on forest soils, such as a decrease in nutrient availability (mainly due to increased exportation of nutrients), which could lead to a reduction in site fertility and tree growth, thereby reducing, in the long term, carbon sequestration rate in the biomass of trees. Clarke et al. (2015) showed that the reduction in SOC stock after harvesting, observed in the organic layer of forests, depended on soil types, climatic conditions and tree species. For all these reasons, forest thinning may decrease carbon stocks in forest soil and in vegetation, increasing soil CO_2 efflux at different degrees (Houghton 2003; Mäkipää et al. 2014). Some studies, however, reported little differences in live tree C when stands that were thinned from below were compared with unmanaged stands (Hurteau and North 2009). These contrasting results demonstrated the importance of ecosystem-specific studies to examine the impact of a variety of silvicultural options on total ecosystem carbon stocks.

In Italy, thinning of pine forests is the most effective silvicultural treatment to enhance the economic value of these stands (Cantiani and Chiavetta 2015). Therefore, this research aims to understand how thinning affects the dynamic of total carbon as well as each of its component pools in *Pinus laricio* forest ecosystem in Aspromonte Mountain (Calabria). We estimated carbon stocks in *Pinus laricio* stands, evaluating carbon pool dynamics in forest subject to different thinning (no thinning, moderate and intense thinning) and clear cut over two contrasting seasons (winter and summer) in order to verify whether environmental conditions affected in a short-term soil carbon pools. Our aim was also to identify the silvicultural practice that best increased and/or maintained carbon storage in pine forest. Our hypothesis was that by increasing thinning intensities, the properties of soil related to fertility and quality could decrease, while the stand stability, wood quality, diameter and volume growth of the remaining stand could improve.

Materials and methods

Study area

The study area, located in 60-year-old natural regenerated *Pinus laricio* stands in Aspromonte Mountain (Zervò, Calabria) (38°24′24″N; 16°01′82″E) at an elevation of 1100 m a.s.l., covers 190 ha. A typically Mediterranean climate prevailed in the study area, with an annual mean temperature of around 10 °C, with minimum and maximum monthly means of 3 °C (coldest month) and 17 °C (warmest month). The annual rainfall is 1838 mm, with minimum precipitation in summer. Rainfalls are unevenly distributed over the year. According to Pavari's phytoclimatic classification (Pavari 1959), the stands belong to the *Castanetum* zone. The soils, developed from high-rank metamorphic rocks, such as schist and biotitic gneisses, were classified according to the IUSS WRB (2006) as Humic Cambisols, with a xeric soil regime moisture. In 2010 started the forest management of this stand. A study area of approximately 45 ha was set up for the plot investigation. The 45 ha were split as follows among the four treatments: (1) 15 ha for the no thinning (T0: control, 1935 N ha^{-1}); 10 ha for the moderate thinning [T25: 25% basal area (BA) removal 1354 N ha^{-1}]; 10 ha for the intense thinning (T45: 45% BA removal 780 N ha^{-1}); and 10 ha for clear cut (CC: 100% thinning, 0 N ha^{-1}). The experimental design was randomized and consisted of five blocks in each site. Each block in the T0 was 3 ha, while in the T25, T45 and CC was 2 ha. Thinnings were designed to reduce stand density, removing all of the trees present in the stand. Residues were removed after the different levels of thinning to reduce summer fire risks and the decay rate of biomass to mitigate environmental pollution in Mediterranean areas.

Soil sampling

Soil sampling was carried out in two different seasons (summer and winter 2014), which differ in soil moisture, soil temperature, soil microbial biomass, etc. Soil samples (0–30 cm) were randomly taken using a soil borer from 3 points within 20 × 20 m quadrat (5) of each block, after removing the litter layers. A total of 120 samples were collected. Physicochemical properties of soil were detected on air-dried, sieved (2 mm mesh) soils. Soil water content (WC) and microbial biomass were detected in fresh soil samples within 24 h of sample collection.

Soil chemical and physical analysis

Particle size analysis was carried out by the hydrometer method, using sodium hexametaphosphate as a dispersant (Boujoucos 1962); pH was measured in distilled water and 1 M KCl using a 1:2.5 (soil:water) suspension; soil total nitrogen (N) was determined by Kjeldahl's procedure (Bremner and Mulvaney 1982), and cation exchange capacity (CEC) was determined by using the barium chloride-triethanolamine method (Mehlich 1953). Electrical conductivity (EC) was detected according to the method described by Blakemore et al. (1987): 10 g of dry soil was put into a glass beaker and mixed with 50 mL of deionized H_2O, the suspension was shaken for 30 min, and after decantation, the conductivity was measured by using a conductometer. The water content was determined by drying the soil to constant weight in oven at temperature 105 °C and measuring the soil sample mass after and before drying. The water mass (or weight) is the difference between the weights of the wet and oven dry samples.

Total soil organic carbon (TOC) was determined according to Springer and Klee (1954). The content of organic carbon was calculated by back-titration with a solution of 0.2 N $FeSO_4$.

For total extractable organic carbon (TEC) determination, each soil sample (5 g) was extracted by adding 100 mL of 0.1 N NaOH/0.1 N $Na_4P_2O_7$ solution at 65 °C for 48 h, under N_2 atmosphere. TEC was fractioned into humified (humic acid, HA + fulvic acid, FA) and non-humified (NH) fractions (Ciavatta et al. 1990). Humic and fulvic acid carbon (HA + FA) determination was performed as reported above, on 10 mL of 0.5 N NaOH solutions (Ciavatta and Govi 1993).

Humification parameters, such as humification index (HI), humification rate (HR) and degree of humification (DH), are calculated as shown in Eqs. 1–3 (Ciavatta et al. 1990):

$$HI = NH/(HA + FA) \quad (1)$$

$$HR\% = 100(HA + FA)/TOC \quad (2)$$

$$DH\% = 100(HA + FA)/TEC \quad (3)$$

"HI" represents the ratio between not humified and humified extracted carbon, while HR is the percent of humification rate and DH is the percent of humified carbon in the extract. Humification index is normally 0.5 or more and may even reach 1 with slightly humified extracted organic matter. The HR % parameter is proportional to the state of humification of the soil organic matter. The DH % is 100% when the extracted organic carbon is completely humified (NH = 0) and 50% if HI = 1. However, when the extracted organic carbon is very humified, the index is close to zero (Gigliotti et al. 1999).

Water-soluble phenols (WSPs) were extracted with distilled water (Kaminsky and Muller 1978) and determined by using the Folin–Ciocalteu reagent, following the method of Box (1983). Tannic acid was used as a standard, and the concentration of water-soluble phenolic compounds was expressed as tannic acid equivalents (μg TAE g^{-1} dry soil).

Soil biochemical analysis

Microbial biomass C was determined by the chloroform fumigation-extraction procedure (Vance et al. 1987). The filtered soil extracts of both fumigated and unfumigated samples were analyzed for soluble organic C using the method of Walkley and Black (Nelson and Sommers 1982).

Microbial activity was determined by the hydrolysis of fluorescein 3,6-diacetate (FDA) into fluorescein, according to Adam and Duncan (2001). The enzyme activity was expressed in μg fluorescein g^{-1} soil h^{-1}. Dehydrogenase (DH) activity was determined by the method of von Mersi and Schinner (1991). Protease (PRO) activity was determined on 1 g (fresh weight) according to the method of Nannipieri et al. (1980). Catalase activity (CAT) was measured by the method of Beck (1971). Results were expressed as μmol O_2 g^{-1} soil min^{-1}.

Soil microbial analysis

Soil bacteria, fungi and actinomycetes were extracted following the method of Elliott and Des Jardin (1999). Total bacteria, fungal and actinomycetes colonies were estimated following the methods of Picci and Nannipieri (2003) and Eaton et al. (2005).

Tree analysis

We analyzed the trees within each 20 × 20 m quadrat plot for all the silvicultural treatments that provided any trees for sampling.

In detail, the following dendrometric parameters: stand density (SD, N ha^{-1}); diameter at breast height (DBH, cm); height (H, m); dominant height (DH, m); basal area (BA, m^2 ha^{-1}); volume (V, m^3 ha^{-1}); arithmetic DBH (cm); arithmetic height (m); quadratic mean diameter (QMD, cm); ratio H/D (adimensional); and wood density (WD, g cm^{-3}) were measured immediately after thinning (2010) and 4 years after thinning (2014).

The dendrometric analyses were carried out with standard methods. The DBH was measured by caliper, while the total height of all the trees was measured with Vertex ultrasonic measuring device. By using these dendrometric parameters, it was possible to determine the H/D ratio indicating population mechanical stability.

Wood density analysis

Wood samples were collected by using an increment borer to extract a section of wood tissue from a living tree with relatively minor injury to the plant itself at a steam breast height. The wood samples were stored in a conditioning chamber (12 h, 20 °C, 50% RH). The wood density was measured with a X-ray densitometer to make a noninvasive analysis. The radiographic image was obtained by using LabVIEW v. 6i (National Instruments) software. Wood X-ray densitometry is a radiation detection method in which X-ray attenuation is converted to wood density (Fellin 2005).

Statistical analysis

All sets of experiments were repeated five times. All statistical analyses were performed using Systat v. 8.0 software package (SPSS Inc., Evanston, IL, USA). All datasets were tested for normality using Shapiro–Wilk and Jarque–Bera tests. Treatment means were compared using Tukey's test (Sokal and Rohlf 1981) to determine which means differed significantly at $p \leq 0.05$. One-way analysis of variance (one-way ANOVA) was used to test the differences in soil and plant quality under different thinnings. Two-way ANOVA was used to test relationships between treatments and seasons. Significant differences and effects were determined as $p \leq 0.05$.

Results

Soil physical features

All the soils analyzed belong to the sandy-loam textural class, with 10% silt, 8% clay and 82% sand. Our results showed that soil texture did not change over seasons and over treatments (data not shown).

pH measured in H_2O was slightly acid in all treatments and ranged between 4.99 and 5.25 in summer, and 5.53 and 5.68 in winter. Treatments did not significantly affect soil pH ($p = 0.4$); however, significant differences were detected between the two seasons, with higher pH values ($p < 0.05$) in winter than in summer (Fig. 1).

Water content significantly differed among the treatments and between the seasons ($p < 0.05$), with the highest values in winter, in the CC treatment. Electrical conductivity significantly differed ($p < 0.05$) among treatments in both summer and winter seasons, with the highest values in winter (Fig. 1). Analysis of variance showed that seasonal variations affected EC and WC more than treatments; the interactions of the two factors, treatment and season, had the lowest effect with respect to the factors individually considered (Table 1).

Soil chemical features

The analyzed soil chemical properties in each thinned stand had the highest values in the summer season, except for N and WSP. Conversely, in unthinned forest soil, the values of OM, CAT and CEC were significantly lower in summer than in winter (Table 2).

The greatest amount of OM was detected in the T45 with values of 24.21% in summer and 15.54% in winter, respectively (Table 2). Analysis of variance showed that treatments affected OM more than seasons and that the interactions of the two factors (treatment and season) had the lowest effect compared to the factors individually considered (Table 3). Similar behavior was observed for microbial biomass C. The maximum MBC amount was recorded in the T45 in summer (7997 μg C g^{-1} dry soil), and the lowest one was detected in T0 in winter (6027 μg C g^{-1} dry soil) (Table 2). Soil C/N value ranged from 9 to 19.5; the highest values were found in summer in the T45 and the lowest one in winter in CC. The interactions of the two factors (treatment and season) were not significant compared to the factors individually considered ($p = 0.1$). The highest FDA activity was detected in the T45, both in summer and in winter seasons, followed by the T25 (Table 2). The lowest FDA activity was found in T0 in both seasons. A similar behavior was observed for PROT, CAT and DH. Analysis of variance showed that treatments affected FDA and CAT more than seasons; on the contrary, seasons affected PROT and DH more than treatments; the interactions of the two factors, treatment and season, had less impact than the factors individually considered (Table 4). WSP differed significantly between the two seasons ($p < 0.05$) but not among the treatments ($p = 0.4$); WSP amount was higher in winter than in summer (Table 2). Regarding TOC, TEC and C_{HA+FA}, the ranking was in the order T45 > T25 > CC > T0, both in summer and in winter seasons. HA/FA ranking was as follows T25 ≥ CC > T0 > T45. In the T45, the HR and DR were the highest in summer and winter, while HI was the lowest (Table 5).

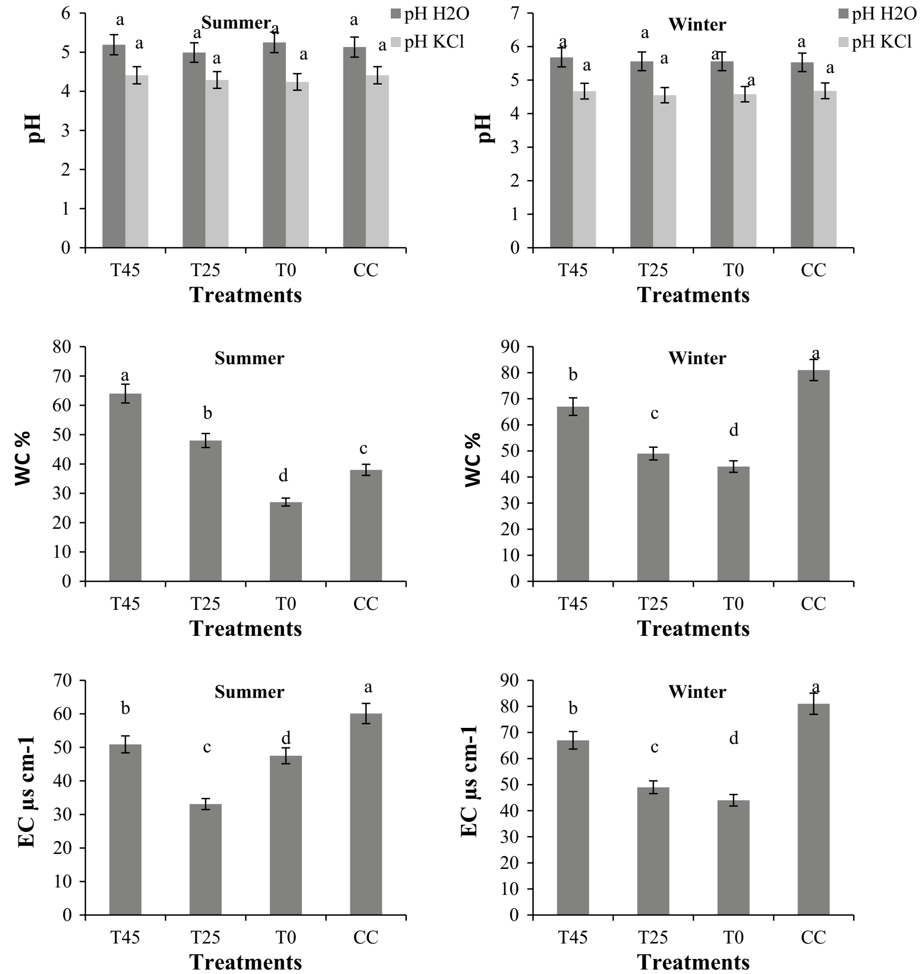

Fig. 1 Physical soil analysis: water content (WC%), pH (H_2O), pH (KCl) and electrical conductivity (EC µs cm^{-1}) under *Pinus laricio* plantation differently managed: intense thinning, T45; moderate thinning, T25; no thinning, T0; and clear cut, CC. Treatments marked with the same letter are not significantly different ($p > 0.05$)

Table 1 Analysis of variance of the effects of treatments, seasons and their interactions on physical and chemical soil parameters: water content (WC); pH (H_2O); pH (KCl); electrical conductivity (EC)

	WC	pH (H_2O)	pH (KCl)	EC
R^2	0.937	0.206	0.129	0.969
F ratio				
Treatments	87.381*	0.745	0.405	219.838*
Seasons	128.571*	7.168*	4.494*	502.219*
Interaction	66.667*	0.329	0.073	25.903*

* $p < 0.05$

Soil microbial features

In all sites, microbial population was significantly higher in summer than in winter, bacteria were more abundant than fungi and no actinomycetes were found. T45 was the most effective treatment that significantly increased the colonies of bacteria in summer and in winter; the ranking was as follows: T45 > T25 > CC > T0 (Fig. 2). Analysis of variance showed that seasons affected fungal and bacterial populations more than treatments; the interactions of the two factors, treatment and season, had the highest effect than the factors individually considered on fungal population, and the lowest ones on bacterial population with respect to the factors individually considered (Table 6).

Tree parameters

Volume, basal area, DBH and height increased, but H/D ratio decreased within the 4 years after thinning at all sites. The greatest increment was observed in T45. The H/D ratio in the T45 decreased most followed by T25 and T0, although it already started with the lowest value of all stands (Table 7). Additionally, wood density increased 4 years after thinning in T45 and T25 more than T0.

Discussion

Carbon storage in soils is a dynamic balance between input of organic matter and output mostly in the form of CO_2 efflux (Tian et al. 2010). The overall response of forest ecosystems,

Table 2 Chemical and biochemical soil analysis: organic matter (OM, %), total nitrogen (N, %), C/N ratio, fluorescein diacetate (FDA, μg fluorescein g^{-1} soil h^{-1}) protease (PROT, μg tyrosine g^{-1} dry soil/2 h), catalase (CAT, μmol O_2 g^{-1} soil min^{-1}), dehydrogenase (DHA, μg TTF g^{-1} h^{-1}), microbial biomass C (MBC, μg C g^{-1}dry soil), water-soluble phenols (WSP μg TAE g^{-1} dry soil) and cation exchange capacity (CEC, meq 100 g^{-1} dry soil) under *Pinus laricio* plantation differently managed: intense thinning, T45; moderate thinning, T25; no thinning, T0; and clear cut, CC

Season	OM	N	C/N	FDA	PROT	CAT	DHA	MBC	WSP	CEC
Summer										
T45	24.21[a]	0.72[a]	19.5[a]	71.92[a]	90.90[a]	1.88[a]	11.15[a]	7997[a]	200[a]	39.2[a]
T25	18.35[b]	0.63[c]	16.5[b]	58.52[b]	80.35[b]	1.69[b]	7.36[b]	7574[b]	200[a]	34.3[b]
T0	7.68[d]	0.37[d]	12[c]	45.86[d]	68.22[d]	0.74[d]	5.89[d]	6378[d]	200[a]	18.5[c]
CC	16.86[c]	0.62[b]	15.8[b]	53.18[c]	76.07[c]	1.13[c]	6.23[c]	6810[c]	195[a]	33.5[b]
Winter										
T45	15.54[a]	0.70[b]	13[a]	61.80[a]	63.01[a]	1.41[a]	4.40[a]	7550[a]	222[a]	31.3[a]
T25	14.49[b]	0.69[b]	12[b]	53.25[b]	59.86[b]	1.32[b]	3.77[b]	6800[b]	233[a]	31.4[a]
T0	12.32[d]	0.67[b]	11[c]	42.85[d]	52.79[d]	0.94[d]	1.93[d]	6027[d]	229[a]	28.0[b]
CC	13.48[c]	0.83[a]	9[d]	50.10[c]	56.81[c]	1.03[c]	2.24[c]	6352[c]	228[a]	30.0[a]
Replicates	5	5	5	5	5	5	5	5	5	5
Factors	*p* value	*p* value	*p* value	*p* value	*p* value	*p* value	*p* value	*p* value	*p* value	*p* value
Results of ANOVA										
Season	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Treatment	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	= 0.4	< 0.05
Interactions	< 0.05	< 0.05	= 0.1	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	= 0.4	< 0.05

Different letters in the same column indicate, within each season, significant differences (Tukey's test, $p \leq 0.05$)

Table 3 Analysis of variance of the effects of treatments, seasons and their interactions on chemical soil parameters: organic matter (OM), water-soluble phenols (WSP) and total nitrogen (N)

	OM	WSP	N
R^2	0.923	0.391	0.424
F ratio			
Treatments	90.167*	0.228	45.373*
Seasons	55.566*	24.304*	24.999*
Interaction	31.332*	0.236	14.217*

* $p < 0.05$

Table 4 Analysis of variance of the effects of treatments, seasons and their interactions on biological soil parameters: fluorescein diacetate (FDA), protease (PROT), catalase (CAT), dehydrogenase (DHA) and microbial biomass C (MBC)

	FDA	PROT	CAT	DHA	MBC
R^2	0.892	0.950	0.763	0.874	0.653
F ratio					
Treatments	97.761*	19.957*	34.420*	74.902*	21.497*
Seasons	23.271*	203.537*	8.479*	504.224*	7.616*
Interactions	4.899*	11.125*	5.592*	5.040*	1.069

* $p < 0.05$

as C source and/or sink, is variable according to forest type, development stage and silvicultural management (Johnson 1992; Nilsen and Strand 2008). Many studies reported that silvicultural management practices may affect directly and/or indirectly C dynamics in forest ecosystems (Johnson 1992; Neary et al. 1999; Balboa-Murias et al. 2006; Nilsen and Strand 2008; Suzanne et al. 2009). Recent studies synthesized evidence regarding forest management effects on soil organic carbon (Lal 2005; Jandl et al. 2007), but quantitative information are limited to specific management issues. The ability of forest soils to sequester C is due to the deposition and accumulation of a resistant slowly decomposable C pool that was estimated to represent approximately 65% of the organic matter in soil. Forest management can change this belowground process (Tang et al. 2005), with consequent negative effects on nutrient concentrations (Ashagrie et al. 2007), water retention (Resck et al. 2008) and carbon storage (Lal 2006). Roscoe and Buurman (2003) quantified the effects of forest management on soil estimating only total organic carbon, but often the changes management-induced are not duly reflected in TOC values; thus, parallel determination of stable and labile fractions of soil organic matter (SOM) would be very useful as already suggested by de Figueiredo et al. (2010). Simultaneous examination of changes in SOM fractions and in soil biological properties can give important information about the impact that

Table 5 Effect of intense thinning, T45; moderate thinning, T25; no thinning, T0; and clear cut, CC on total organic carbon (TOC), total extractable carbon (TEC), humic acid plus fulvic acid carbon C_{HA+FA}, humic acid/fulvic acid (HA/FA), humification index (HI), humification rate (HR), humification degree (DR)

Season	TOC (%)	TEC (%)	C_{HA+FA} (%)	HA/FA	HI	HR (%)	DR (%)
Summer							
T45	14.07[a]	12.6[a]	10.83[a]	1.17[c]	0.16[d]	77.0[a]	85.9[a]
T25	10.66[b]	8.4[b]	6.77[b]	1.42[a]	0.24[c]	63.5[b]	80.5[b]
T0	4.46[d]	3.3[d]	2.61[d]	1.25[b]	0.26[b]	58.5[c]	79.1[b]
CC	9.80[c]	7.6[c]	5.56[c]	1.43[a]	0.37[a]	56.7[c]	73.1[c]
Winter							
T45	9.03[a]	7.8[a]	6.85[a]	1.22[d]	0.14[d]	75.3[a]	87.5[a]
T25	8.42[b]	6.6[b]	4.95[b]	1.96[a]	0.33[b]	58.8[c]	75.2[c]
T0	7.16[d]	5.3d	3.85[c]	1.58[c]	0.38[a]	53.5[d]	72.1[c]
CC	7.83[c]	6.2[c]	5.0[b]	1.67[b]	0.24[c]	63.3[b]	80.7[b]
Replicates	5	5	5	5	5	5	5
Factors	*p* value	*p* value	*p* value	*p* value	*p* value	*p* value	*p* value
Results of ANOVA							
Season	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	=0.4	=0.4
Treatment	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Interaction	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

Different letters in the same column indicate, within each season, significant differences (Tukey's test, $p \leq 0.05$)

forest management have on C cycle (Sicardi et al. 2004; Sidari et al. 2005). It has been well demonstrated that soil ecosystems with large microbial communities improve soil carbon sequestration more than soil ecosystem with reduced biodiversity (de Graaff et al. 2015). Increasing evidence in the literature indicates that taxonomic and functional compositions of microbial communities are strong drivers of SOM processes (Hooper et al. 2005). Fungal hyphae and polysaccharides microbial-originated produce organic polymers, which form and stabilize aggregates, playing an important role in building and conserving soil structure (Darbyshire et al. 1993). Additionally, soil bacteria have been identified as a functional group in driving soil organic matter dynamic (Nannipieri et al. 2003; Fierer et al. 2007). Soil bacterial communities are strongly linked to the extracellular enzymes involved in carbon transformation, whereas fungi are associated with activities of extracellular enzymes driving carbon oxidation (You et al. 2014). Under T45, the soils had the highest amount of microbial biomass and bacteria. These results qualitatively demonstrated a microbial diversity–SOM dynamics relationship. These data were also confirmed by the results of enzymatic activities. Soil enzymes play an important role in organic matter decomposition and nutrient cycling. Several studies showed that enzyme activities can be used as early indicators of changes in soil properties originated by management practices and consequences of global changes (Deng and Tabatabai 1994; Kandeler et al. 1999; Ajwa et al. 1999; Alvear et al. 2005; Muscolo et al. 2014, 2015). Our results showed an increase in all enzymatic activities in managed soils, mostly in the T45, supporting previous findings of Jiménez et al. (2016), indicating that soil with great diversity and amount of ground vegetation had greater enzymatic activity. The seasonality influenced soil carbon sequestration, and in summer time, in agreement with previous results of Rowland et al. (2014), we observed the greatest amount of OM, TOC, TEC and the highest values of HI, HR and DR in each forest treatment. The ranking effects of treatments on soil were instead the same in summer and winter. Our results evidenced that seasons affected soil carbon storage less than treatments, suggesting that the lower density of trees in the T45 resulted in different regimes of light, temperature and humidity at the ground and in the soil, increasing herbaceous vegetation and easily degradable litter, which in turn promoted an increase in soil microbial biomass and overall in bacteria amount. Our results are in agreement with the findings of Bardgett et al. (2003), Lee and Jose (2003), Allison (2006), De Deyn et al. (2009) and Billings et al. (2010), showing that microbes are largely responsible for the cycling of plant-available soil nutrients and for the decomposition of organic matter and soil carbon sequestration, affecting the ratio of carbon converted to carbon dioxide or to soil organic carbon. We found that T45 was the practice that mostly increased the stable fraction of SOM and the humification ratio, the degree of humification, while decreased the humification index. All together these humification parameters indicated that the T45 was the silvicultural practice to adopt for increasing soil carbon storage.

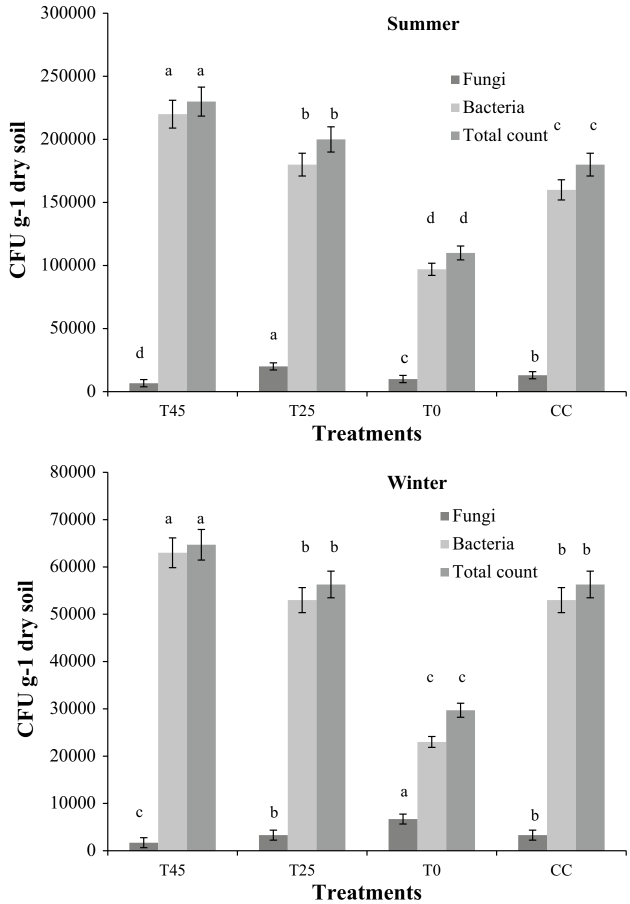

Fig. 2 Colonies of fungi and bacteria (CFU g^{-1} dry soil) in soil under *Pinus laricio* plantation differently managed: intense thinning, T45; moderate thinning, T25; no thinning, T0; and clear cut, CC. Treatments marked with the same letter are not significantly different ($p > 0.05$)

Pinus growth (diameter and height) and wood density changed with the treatments. H/D ratio in T45 was lower than in T25 and T0, suggesting that the positive effect of the T45 on the mechanical stability of the trees is due to a large accumulation of wood distributed more in the diameter rather than in the height. Additionally, an increment in basal area and wood density suggested that T45 was the best practice for pinus growth. In short, we can suggest that the T45 is able to increase C concentration both in *Pinus laricio* tree and in soil, with evident effects 4 years after thinning.

Table 6 Analysis of variance of the effects of treatments, seasons and their interactions on fungi and bacteria colonies in soil under *Pinus laricio*

	Fungi	Bacteria
R^2	0.985	0.978
F ratio		
Treatments	263.438*	326.250*
Seasons	408.437*	540.000*
Interaction	1020.938*	97.500*

* $p < 0.05$

Conclusions

Our study provides scientific information for establishing the role of pine forest soils in carbon sequestration programs, predicting the consequences of current management practices for future forest productivity, and understanding how ecological processes interact with human interventions to influence soil carbon storage. These results are important for land managers policymakers, carbon accountants and scientists working on a variety of forest-related issues. Our challenge is now to expand our knowledge to other forests so that we can predict the dynamic behavior of soil processes and the impact of management practices on carbon storage. Ability to meet this challenge will play a key role in determining the sustainability of forest management activities.

Table 7 Dendrometric parameters: stand density (SD, Nha^{-1}); diameter at breast height (DBH, cm); height (H, m); dominant height (DH, m); basal area (BA, m^2 ha^{-1}); volume (V, m^3ha^{-1}); arithmetic DBH (cm); arithmetic height (m); quadratic mean diameter (QMD, cm); ratio H/D (adimensional); wood density (WD, g cm^{-3}) of *Pinus laricio* trees differently managed: intense thinning, T45; moderate thinning, T25; no thinning, T0; and clear cut, CC

Year	Thinning intensities	SD	DBH	H	DH	BA	V	Arithmetic DBH	Arithmetic H	QMD	H/D	WD
2010	T45	780	25.6^a	20.2^a	21.0^a	46.5^c	532.4^c	27.5^a	19.1^a	27.55^a	78.9^b	0.53^a
	T25	1354	23.1^b	20.0^a	20.7^a	60.3^b	698.3^b	23.4^b	18.9^a	23.81^b	86.6^a	0.51^{ab}
	T0	1935	21.4^c	18.0^b	19.1^b	77.3^a	748^a	22.2^c	17.1^b	22.55^c	84.1^a	0.49^b
2014	T45	780	30.3^a	20.8^a	22.2^a	54.1^c	562.4^b	31.3^a	19.2^a	29.71^a	68.6^b	0.58^a
	T25	1354	26.9^b	20.9^a	21.4^a	68.9^b	728.4^a	27.3^b	19.3^a	25.45^b	77.6^a	0.53^b
	T0	1935	23.6^c	18.4^b	20.1^b	84.5^a	774.8^a	24.4^c	16.7^b	23.57^c	77.9^a	0.52^b

Different letters in the same column indicate, within each season, significant differences (Tukey's test, $p \leq 0.05$)

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References

Achat DL, Fortin M, Landmann G, Ringeval B, Augusto L (2015) Forest soil carbon is threatened by intensive biomass harvesting. Sci Rep 5(1–10):15991

Adam G, Duncan H (2001) Development of a sensitive and rapid method for the measurement of total microbial activity using fluorescein diacetate (FDA) in a range of soils. Soil Biol Biochem 33:943–951

Ajwa HA, Dell CJ, Rice CW (1999) Changes in enzyme activities and microbial biomass of tallgrass prairie soil as related to burning and nitrogen fertilization. Soil Biol Biochem 31:769–777

Alemu B (2014) The role of forest and soil carbon sequestrations on climate change mitigation. J Environ Earth Sci 4:98–111

Allison SD (2006) Soil minerals and humic acids alter enzyme stability: implications for ecosystem processes. Biogeochemistry 81:361–373

Alvear M, Rosas A, Rouanet JL, Borie F (2005) Effects of three soil tillage systems on some biological activities in an Ultisol from southern Chile. Soil Till Res 82:195–202

Ashagrie Y, Zech W, Guggenberger G, Miano T (2007) Soil aggregation, and total and particulate organic matter following conversion of native forests to continuous cultivation in Ethiopia. Soil Till Res 94:101–108

Balboa-Murias MA, Rodríguez-Soalleiro R, Merino A, Álvarez-González JG (2006) Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives. For Ecol Manage 237:29–38

Bardgett RD, Streeter TC, Bol R (2003) Soil microbes compete effectively with plants for organic-nitrogen inputs to temperate grasslands. Ecology 84:1277–1287

Beck T (1971) Die Messung der Katalaseaktivität von Böden. Z Pflanzenernähr Bodenkd 130:68–81

Billings SA, Lichter J, Ziegler SE, Hungate BA, de Richter BD (2010) A call to investigate drivers of soil organic matter retention versus mineralization in a high CO_2 world. Soil Biol Biochem 42:665–668

Birdsey R, Pregitzer K, Lucier A (2006) Forest carbon management in the United States: 1600–2100. J Environ Qual 35:1461–1469

Blakemore LC, Searle PL, Daly BK (1987) Methods for chemical analysis of soils. New Zealand Soil Bureau, Scientific report, p 80

Boujoucos GJ (1962) Hydrometer method improved for making particle size analysis of soils. J Agron 54:464–465

Bowden RD, Davidson E, Savage K, Arabia C, Steudler P (2004) Chronic nitrogen additions reduce total soil respiration and microbial respiration in temperate forest soils at the Harvard forest. For Ecol Manage 196:43–56

Box JD (1983) Investigation of the Folin—Ciocalteau reagent for the determination of polyphenolic substances in natural waters. Water Res 17:511–525

Bradford J, Weishampel P, Smith M, Kolka R, Birdsey RA, Ollinger SV, Ryan MG (2009) Detrital C pools in temperate forests: magnitude and potential for landscape-scale assessment. Can J For Res 39:802–813

Bremner JM, Mulvaney CS (1982) Nitrogen-total. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis: Part 2-chemical and microbiological properties, 2nd edn. Soil Science Society of America, Madison, pp 595–624

Cantiani P, Chiavetta U (2015) Estimating the mechanical stability of *Pinus nigra* Arn. using an alternative approach across several plantations in central Italy. iForest 8:846–852

Chapin FS, Matson PA, Vitousek PM (2011) Principles of terrestrial ecosystem ecology. Springer, New York

Ciavatta C, Govi M (1993) Use of insoluble polyvinylpyrrolidone and isoelectric focusing in the study of humic substances in soils and organic wastes: a review. J Chromatogr 643:261–270

Ciavatta C, Govi M, Vittori Antisari L, Sequi P (1990) Characterization of humified compounds by extraction and fractionation on solid polyvinylpyrrolidone. J Chromatogr 509:141–146

Clarke N, Gundersen P, Jönsson-Belyazid U, Kjønaas OJ, Persson T, Sigurdsson BJ, Stupak I, Vesterdal L (2015) Influence of different tree-harvesting intensities on forest soil carbon stocks in boreal and northern temperate forest ecosystems. For Ecol Manage 351:9–19

Darbyshire JF, Chapman SJ, Cheshire MV, Gauld JH, McHardy WJ, Paterson E, Vaughan D (1993) Methods for the study of interrelationships between micro-organisms and soil structure. In: Brussard L, Kooistra MJ (eds) Soil structure/soil biota relationships. Elsevier, Amsterdam

Davis SC, Hessl AE, Scott CJ, Adams MB, Thomas RB (2009) Forest carbon sequestration changes in response to timber harvest. For Ecol Manage 258:2101–2109

De Deyn GB, Quirk H, Yi Z, Oakley S, Ostle NJ, Bardgett RD (2009) Vegetation composition promotes carbon and nitrogen storage in model grassland communities of contrasting soil fertility. J Ecol 97:864–875

de Figueiredo CC, Resck DVS, Carneiro MAC (2010) Labile and stable fractions of soil organic matter under management systems and native Cerrado. Rev Bras Ciênc Solo 34:907–916

de Graaff MA, Adkins J, Kardol P, Throop HL (2015) A meta-analysis of soil biodiversity impacts on the carbon cycle. Soil 1:257–271

Deng SP, Tabatabai MA (1994) Cellulase activity in soils. Soil Biol Biochem 26:1347–1354

Eaton AD, Clesceri LS, Greenberg AW (2005) Standard methods for the examination of water and wastewater. APHA, Washington, DC

Elliott ML, Des Jardin EA (1999) Comparison of media and diluents for enumeration of aerobic bacteria from bermuda grass golf course putting greens. J Microbiol Methods 34:193–202

Fellin M (2005) Radio-densitometry of wood: calibration and characterization of an experimental laboratory device. Dissertation, University of Padova

Fierer N, Bradford MA, Jackson RB (2007) Toward an ecological classification of soil bacteria. Ecology 88:1354–1364

Gigliotti G, Businelli D, Giusquiani PG (1999) Composition changes of soil humus after massive application of urban waste compost: a comparison between FT-IR spectroscopy and humification parameters. Nutr Cycl Agroecosyst 55:23–28

Gough CM, Vogel CS, Schmidt HP, Curtis PS (2008) Controls on annual forest C storage: lessons from the past and predictions for the future. Bioscience 58:609–621

Hooper DU, Chapin FS III, Ewel JJ, Hector A, Inchausti P, Lavorel S, Lawton JH, Lodge DM, Loreau M, Naeem S, Schmid B, Setälä H, Symstad AJ, Vandermeer J, Wardle DA (2005) Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecol Monogr 75:3–35

Houghton RA (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus B 55:378–390

Hurteau M, North M (2009) Fuel treatment effects on tree-based forest C storage and emissions under modeled wildfire scenarios. Front Ecol Environ 7:409–414

IUSS Working Group WRB (2006) World reference base for soil resources 2006. World soil resources reports no. 103. FAO, Rome

Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz R, Hagedorn F, Johnson DW, Minkkinen K, Byrne KA (2007) How strongly can forest management influence soil carbon sequestration? Geoderma 137:253–268

Jassal RS, Black TA, Cai T, Morgenstern K, Li Z, Gaumont-Guay D, Nesic Z (2007) Components of ecosystem respiration and an estimate of net primary productivity of an intermediate-aged Douglas-fir stand. Agric For Meteorol 144:44–57

Jimenez RMD, Fita A, Burruezo AR (2016) Geophysical research abstracts Vol. 18, EGU 2016-14848, Enzyme activities by indicator of quality in organic soil. EGU General Assembly 2016

Johnson DW (1992) Effects of forest management on soil carbon storage. Water Air Soil Pollut 64:83–120

Kaminsky R, Muller WH (1978) A recommendation against the use of alkaline soil extraction in the study of allelopathy. Plant Soil 49:641–645

Kandeler E, Palli S, Stemmer M, Gerzabek MH (1999) Tillage changes microbial biomass and enzyme activities in particle size fractions. Soil Biol Biochem 31:1253–1264

Keith H, Jacobsen KL, Raison RJ (1997) Effects of soil phosphorus availability, temperature and moisture on soil respiration in *Eucalyptus pauciflora* forest. Plant Soil 190:127–141

Kim C, Son Y, Lee WK, Jeong J, Noh NJ (2009) Influences of forest tending works on carbon distribution and cycling in a *Pinus densiflora* S. et Z. stand in Korea. For Ecol Manage 257:1420–1426

Kirschbaum MUF (1996) The carbon sequestration potential of tree plantations in Australia. In: Eldridge KG, Crowe MP, Old KM (eds) Environmental management: the role of Eucalypts and other fast growing species. CSIRO Publishing, Canberra, pp 77–89

Krug G, Koehl M, Kownatzki D (2012) Revaluing unmanaged forests for climate change mitigation. Carbon Balance Manag 7:11

Lal R (2005) Forest soils and carbon sequestration. For Ecol Manage 220:242–258

Lal R (2006) Soil carbon sequestration in Latin America. In: Lal R, Cerri CC, Bernoux M, Etcheves J, Cerri E (eds) Carbon sequestration in soils of Latin America. CRC Press, New York, pp 49–64

Lee KA, Jose S (2003) Soil respiration, fine root production, and microbial biomass in cottonwood and loblolly pine plantations along a nitrogen fertilization gradient. For Ecol Manage 185:263–273

Leung DYC, Caramanna G, Maroto-Valer MM (2014) An overview of current status of carbon dioxide capture andstorage technologies. Renew Sustain Energy Rev 39:426–443

Mäkipää R, Linkosalo T, Komarov A, Mäkelä A (2014) Mitigation of climate change with biomass harvesting in Norway spruce stands: Are harvesting practices carbon neutral? Can J For Res 45:1–9

Mehlich A (1953) Rapid determination of cation and anion exchange properties and pH of soils. J Assoc Off Agric Chem 36:445–457

Muscolo A, Sidari M, Mercurio R (2007a) Gap size effects on above- and below-ground processes in a silver fir stand. Eur J For Res 126:59–65

Muscolo A, Sidari M, Mercurio R (2007b) Influence of gap size on organic matter decomposition, microbial biomass and nutrient cycle in Calabrian pine (*Pinus laricio*, Poiret) stands. For Ecol Manage 242:412–418

Muscolo A, Sidari M, Bagnato S, Mallamaci C, Mercurio R (2010) Gap size effects on above- and below-ground processes in a silver fir stand. Eur J For Res 129:355–365

Muscolo A, Panuccio MR, Mallamaci C, Sidari M (2014) Biological indicators to assess short-term soil quality changes in forest ecosystems. Ecol Ind 45:416–423

Muscolo A, Settineri G, Attinà E (2015) Early warning indicators of changes in soil ecosystem functioning. Ecol Ind 48:542–549

Muscolo A, Settineri G, Bagnato S, Mercurio R, Sidari M (2017) Use of canopy gap openings to restore coniferous stands in Mediterranean environment. iForest 10:322–327

Nannipieri P, Ceccanti B, Cervelli S, Matarese E (1980) Extraction of phosphatase, urease, proteases, organic carbon, and nitrogen from soil. Soil Sci Soc Am J 44:1011–1016

Nannipieri P, Ascher J, Ceccherini M, Landi L, Pietramellara G, Renella G (2003) Microbial diversity and soil functions. Eur J Soil Sci 54:655–670

Neary DG, Klopatek CC, DeBano LF, Ffolliott PF (1999) Fire effects on belowground sustainability: a review and synthesis. For Ecol Manage 122:51–71

Nelson DW, Sommers LE (1982) Total carbon, organic carbon and organic matter. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis: Part 2-chemical and microbiological properties, 2nd edn. Soil Science Society of America, Madison, pp 539–580

Nilsen P, Strand LT (2008) Thinning intensity effects on carbon and nitrogen stores and fluxes in a Norway spruce (*Picea abies* (L.) Karst.) stand after 33 years. For Ecol Manage 256:201–208

North M, Hurteau M, Innes J (2009) Fire suppression and fuels treatment effects on mixed-conifer C stocks and emissions. Ecol Appl 19:1385–1396

Pavari A (1959) Le classificazioni fitoclimatiche ed i caratteri della stazione [Phytoclimatic classifications and station characteristics]. Scritti di ecologia selvicoltura e botanica forestale, pp 45–116

Picci G, Nannipieri P (2003) Metodi di analisi microbiologica del suolo. Franco Angeli Editore, Milano

Pregitzer KS, Euskirchen ES (2004) Carbon cycling and storage in world forests: biome patterns related to forest age. Glob Chang Biol 10:2052–2077

Qiu S, Bell RW, Hobbs RJ, Mccomb AJ (2011) Estimating nutrient budgets for prescribed thinning in a regrowth eucalyptus forest in south-west Australia. Forestry 85:51–61. doi:https://doi.org/10.1093/forestry/cpr054

Resck DVS, Ferreira EAB, Figueiredo CC, Zinn YL (2008) Dinâmica da matéria orgânica no Cerrado. In: Santos GA, Silva LS, Canellas LP, Camargo FO (eds) Fundamentos da matéria organic do solo: Ecossistemas tropicais e subtropicais, 2nd edn. Metrópole, Porto Alegre, pp 359–417

Roscoe R, Buurman P (2003) Tillage effects on soil organic matter in density fractions of a Cerrado Oxisol. Soil Till Res 70:107–119

Rowland L, Hill TC, Stahl C, Siebicke L, Burban B, Zaragoza-Castel J, Ponton S, Bonal D, Meir P, Mathew Williams M (2014) Evidence for strong seasonality in the carbon storage and carbon use efficiency of an Amazonian forest. Glob Chang Biol 20(3):979–991

Ryu SR, Concilio A, Chen J, North M, Ma S (2009) Prescribed burning and mechanical thinning effects on belowground conditions and soil respiration in a mixed-conifer forest, California. For Ecol Manage 257:1324–1332. doi:https://doi.org/10.1016/j.foreco.2008.11.033

Selig MF, Seiler JR, Tyree MC (2008) Soil C and CO_2 efflux as influenced by the thinning of loblolly pine (*Pinus taeda* L.) plantations in the Piedmont of Virginia. Forest Sci 54:58–66

Sicardi M, García-Préchac F, Frioni L (2004) Soil microbial indicators sensitive to land use conversion from pastures to commercial *Eucalyptus grandis* (Hill ex Maiden) plantations in Uruguay. Appl Soil Ecol 27:125–133

Sidari M, Muscolo A, Cianci V, Attinà E, Vecchio G, Zaffina F (2005) Evoluzione della sostanza organica in suoli rappresentativi dell'Altopiano della Sila. Forest@ 2:296–305

Six J, Callewaert P, Lenders S, Gryze SD, Morris SJ, Gregorich EG, Paul EA, Paustian K (2002) Measuring and understanding carbon storage in afforested soils by physical fractionation. Soil Sci Soc Am J 66:1981–1987

Sokal RR, Rohlf FJ (1981) Biometry. Freeman, San Francisco

Springer U, Klee J (1954) Prüfung der leistungsfähigkeit von einigen wichtigen verfahren zur bestimmung des kohlenstoffs mittels chromschwefelsaure sowie vorschlag einer neuen schnellmethode. J Plant Nutr Soil Sci 64:1–26

Sullivan BW, Kolb TE, Hart SC, Kaye JP, Dore S, Montes-Helu M (2008) Thinning reduces soil C dioxide but not methane flux from southwestern USA ponderosa pine forests. For Ecol Manage 255:4047–4055

Suzanne MO, Carolyn HS, Catherine AG, Matthew AB (2009) Above- and belowground responses to tree thinning depend on the treatment of tree debris. For Ecol Manage 259:71–80

Tang J, Qi Y, Xu M, Misson L, Goldstein AH (2005) Forest thinning and soil respiration in a ponderosa pine plantation in the Sierra Nevada. Tree Physiol 25:57–66

Tian DL, Peng YY, Yan WD, Fang X, Kang WX, Wang GJ, Chen XY (2010) Effects of thinning and litter fall removal on fine root production and soil organic carbon content in Masson pine plantations. Pedosphere 20:486–493

Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass C. Soil Biol Biochem 19:703–707

Von Mersi W, Schinner F (1991) An improved and accurate method for determining the dehydrogenase activity of soils with iodonitrotetrazolium chloride. Biol Fertil Soils 11:216–220

Weiskittel AR, Hann DW, Kershaw JA Jr, Vanclay JK (2011) Forest growth and yield modeling. Wiley-Blackwell, Chichester

Whorf TP, Keeling CD (1998) Rising carbon. New Sci 157:54

You Y, Wang J, Huang X, Tang Z, Liu S, Sun OJ (2014) Relating microbial community structure to functioning in forest soil organic carbon transformation and turnover. Ecol Evol 4:633–647

Zhao K, Hao Y, Jia Z, Ma L, Jia F (2014) Soil properties responding to *Pinus tabulaeformis* forest thinning in mountainous areas, Beijing. Adv J Food Sci Technol 6:1219–1227