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Review

Soil organic C as affected by silvicultural and exploitative interventions in *Nothofagus pumilio* forests of the Chilean Patagonia

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ABSTRACT

This study evaluates the effect of silvicultural and exploitative interventions on soil organic carbon (SOC) in Chilean Lenga (*Nothofagus pumilio* (Poepp et Endl.) Krasser) forests in south Patagonia. We analyzed SOC and the organic soil horizons in five stands at different stages of development: intact native forest (NI); a 3-year-old shelterwood stand (S3); an 8-year-old shelterwood stand (S8); a 14-year-old stand that was initially treated with shelterwood and subsequently final cut (10 years after the first intervention) (S14), and a 25-year-old stand subject to a exploitative intervention (E25). The SOC under the forest stands, down to a depth of 50 cm (including the Oi horizon), was 60, 55, 71, 85, and 67 Mg ha^{-1} for the NI, S3, S8, S14, and E25 forest stands, respectively. A significant decrease in SOC occurred 3 years after an intensive shelterwood cut (S3), particularly in the first 5 cm of the mineral soil. Slightly higher carbon contents were observed in the upper horizons of the mineral soil in both the S8 and S14 stands. Consequently, the applied shelterwood system appears to generate only short-term losses of SOC in the Lenga forest. Soil organic carbon increased over the medium term but decreased to the level observed in intact native forests over the long term. Regeneration, which influences stand microclimate (a factor in SOC storage) and provides an important source of organic soil material, was identified as one of the most important factors influencing SOC.

Contents

1. Introduction

Carbon storage in forest soils is influenced by soil texture, microclimate and topography (Post, 1982; Vande Walle et al., 2001; Dilustro et al., 2005). Site preparation, harvest residue management, forest species composition and fire also play an

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important role in soil organic carbon (SOC) balance (e.g., Johnson et al., 2002; Berger, 2002; Lal, 2005). Depending on the applied silvicultural treatment and harvest intensity (Peltoniemi et al., 2004), silviculture can also positively or negatively affect SOC (e.g., Laiho et al., 2003; McLaughlin and Phillips, 2006). Various studies have shown that SOC decreases mostly in the first 10 years after intervention (e.g., Knoepp and Swank, 1997; Mendham et al., 2003). While whole-tree harvesting may cause short-term losses in SOC (e.g., Knoepp and Swank, 1997; Johnson and Curtis, 2001; Laiho et al., 2003), negative long-term effects on SOC storage have not been detected (e.g., Knoepp and Swank, 1997; Johnson et al., 2002; Peltoniemi et al., 2004; McLaughlin and Phillips, 2006). In some cases SOC may increase, particularly where saw-log harvesting is used (e.g., Johnson and Curtis, 2001).

In the Patagonian Lenga forests, most research has focused on the estimation of C in aboveground biomass (e.g., Loguercio and Defossé, 2001; Böswald et al., 2002). Few studies have investigated the effects of silvicultural practices on SOC (e.g., Weber, 2001; Moretto et al., 2005).

The Lenga forests represent the major source of native timber in Chile. These forests are mostly concentrated in the Magallanes Region, where approximately one half (i.e. 500,000–600,000 ha) of the productive forests have not been managed (Schmidt et al., 2003). Currently considered the best silvicultural option for Lenga forests in this region, the shelterwood system is expected to be the primary form of intervention as these forests come under management. Due to the increased levels of atmospheric CO_2, forest management practices should ideally minimize the loss of SOC. However the effects of silvicultural interventions on SOC in Chilean Lenga forests are still unknown. The aim of this study was to evaluate the effects of different forest interventions (including the shelterwood silvicultural system) on SOC in Lenga forests in the Magallanes Region of Chile.

2. Materials and methods

2.1. Study area

Study sites were located near Puerto Natales (Fig. 1), in the Region of Magallanes, Chile (52°05′S–52°10′S, 71°35′W–71°55′W; 430 m above sea level). The region is in the Cold-Temperate zone of the High-Oceanic climates. Maximum and minimum mean annual temperatures are 15.3 °C in January and −0.3 °C in July, respectively. The annual average precipitation of 416 mm is homogenously distributed throughout the year (Caldentey et al., 2001). Soils are derived from glacial drift and volcanic materials with sandy-loam textural classes (Cryochrepts). Rooting systems are mostly concentrated in the A and Bw horizons (upper 40–50 cm depth). Soils under Lenga forests can exhibit podzolization (Aquods and Cryods), characterized by the presence of E and Bhs horizons. The origin of the E horizon is thought to be volcanic ash, altered by eluviation processes (Gerding and Thiers, 2002).

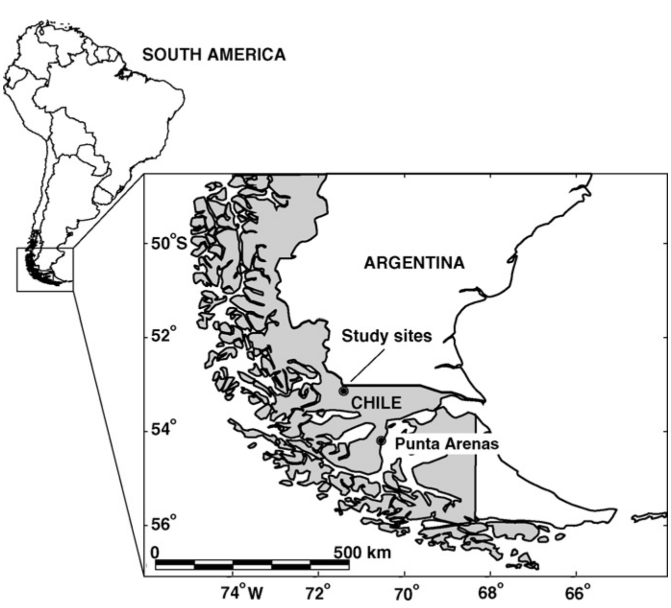

Fig. 1. General location of the study sites.

2.2. Forest stands description

We selected a total of five forest stands (1 ha each in size) at different stages of development (Fig. 2), on the basis of the time since the last intervention: one non-intervened (pristine) stand (NI); two stands that had been subjected to a shelterwood cut 3 and 8 years before this study (S3 and S8, respectively), one stand subjected to both a shelterwood cut and a final cut, 14 and 4 years prior to this study, respectively (S14); and one stand subjected to historical non-silvicultural exploitative tree cutting (high-grading) 25 years prior to this study (E25). The general characteristics of these forest stands are given in Table 1.

2.3. Soil and organic layers sampling

Soil sampling was conducted over January–March in both 2006 and 2007. In each forest stand, 20 sampling points were randomly selected from a set of 36 systematically distributed points (distance between points = 20 m). At each sampling point, we measured the depth of the organic layer (Oi) and manually extracted a litter sample (sampling area = 1 m^2) which was stored in paper bags until laboratory analysis. A 0.25 m^2 soil pit was also dug to a depth of 0.5 m at each sampling point from which disturbed soil samples (approximately 500 g each) were extracted from four depth intervals: 0–5, 5–10, 10–30 and 30–50 cm. For each depth interval, the soil stone content was characterized according to the Munsell® Soil Color Charts for estimating proportions of mottles and coarse fragments. We also collected intact soil cores of 98.18 cm^3 for each depth interval using a manual hammer-driven core sampler. The field soil samples, except core samples, were air-dried, passed through a 2 mm sieve, mixed thoroughly and then stored until laboratory analysis.

Table 1
Main characteristics of sampled stands

	Forest stands				
	NI	S3	S8	S14	E25
V_{pr} [a](m^3 ha^{-1})	653	627	734	811	790
Timber volume (m^3 ha^{-1})	–	255	244	553	256
Harvest intensity (%)	–	41	33	68	32
V_{po} [b](m^3 ha^{-1})	653	372	490	258	534
V_s [c](m^3 ha^{-1})	653	303	406	50	415
Basal $area_{pr}$ (m^2 ha^{-1})	64	62	74	82	81
Basal $area_s$ (m^2 ha^{-1})	64	30	42	5	42
$Density_{pr}$ (trees ha^{-1})	755	627	400	415	437
$Density_{po}$ (trees ha^{-1})	755	204	162	6	251
Stand height [d](m)	22	23	24	24	24

The reduced standing wood volume (*V*) at sampling time in comparison to the standing wood volume directly after intervention is a consequence of wind damage.
[a] Letters 'pr' indicates pre-harvest values.
[b] Letters 'po' indicates post-harvest values.
[c] Letter 's' indicates at time of study.
[d] Determined using height measurement of tallest trees.

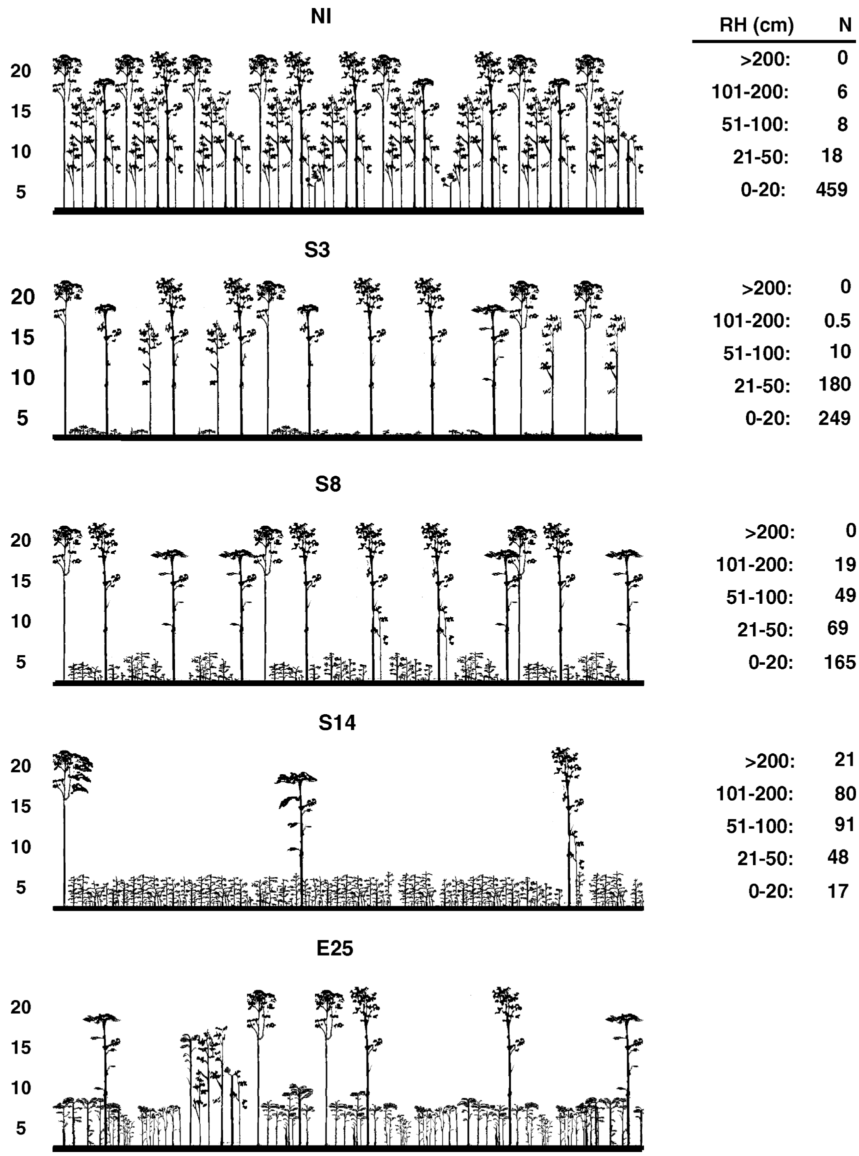

Fig. 2. General drawing of the forests stands during the study. Lenga regeneration has been divided in height classes (RH). ***N*** corresponds to the number of plants (thousands per hectare).

2.4. Laboratory analysis

The organic Oi samples were oven-dried at 65 °C until constant weight was reached, and then weighed. Soil pH was determined by potentiometry in a 1:1 soil to water suspension. Carbon and nitrogen content was measured by dry combustion using an EA 3000 elementary analyzer following DIN ISO 10694. Soil texture was analyzed using the hydrometer method (Gee and Or, 2002). An atomic absorption spectrometer was used to determine effective cation exchange capacity (CEC_e) using NH_4Cl as extractant (PerkinElmer, Waltham, MA). Soil bulk density (ρ_b) was taken from intact soil core samples as the ratio of oven-dried soil weight to cylinder volume.

2.5. Data and statistical analysis

For each sampling depth, soil C and N contents per unit area basis (i.e. $\mathrm{Mg\,ha^{-1}}$) were estimated as

$$C_{ha} = C_{on} \times \rho_b \times H \times S \quad (1)$$

where C_{on} is the nutrient concentration in a dry-weight basis, H is the soil depth interval, and S is a correction factor for stone (>2 mm) content.

Forest stands were analyzed using an unreal time series with a time horizon of 25 years. One-way analysis of variance (ANOVA) was used to test for comparative differences in C content between the forest stands and various soil depths. Assumptions of normality and homogeneity of variances were examined with the Kolmogorov–Smirnov and Levene tests, respectively (Köhler, 1996). Where significant differences ($P < 0.05$) were found, we further analyzed the means using the Tamhane's T2 post hoc test. The ANOVA was carried out using SPSS 13.0 statistical software (SPSS Inc., Chicago, IL). Correlations between SOC and clay content were analyzed using the Pearson's correlation coefficient.

3. Results and discussion

3.1. Basic soil properties

Soil particle distribution was similar among the forest stands with sandy-loam textures predominating in the soil profiles

Table 2
General soil properties under the forest stands

Soil depth (cm)	n	ρ_b [b] ($g\,cm^{-3}$)	f [c]	Particle size distribution [a] (wt. %)				n	Concentration			CEC_e ($cmol_c\,kg^{-1}$)	pH (1:1)
				n	Sand (50–2000 μm)	Silt (2–50 μm)	Clay (< 2 μm)		C_{total} (wt. %)	N_{total} (wt. %)	Exchangeable Al^{3+} ($cmol_c\,kg^{-1}$)		
Non-intervened forest stand (NI)													
Oi								18	46.51 (1.00)	0.80 (0.03)			
0–5	16	0.49 (0.02)	0.82	7	65.6	20.4	14.0	20	8.64 (0.39)	0.37 (0.01)	0.08	19.95	5.5 (0.1)
5–10	16	0.70 (0.04)	0.74	8	72.4	21.4	6.2	19	2.40 (0.13)	0.10 (0.01)	0.49	6.14	5.2 (0.1)
10–30	16	0.76 (0.02)	0.71	7	74.4	20.6	5.0	19	1.79 (0.08)	0.08 (0.01)	1.06	3.02	5.2 (0.1)
30–50	10	0.83 (0.05)	0.69	7	70.7	23.8	5.5	17	1.57 (0.06)	0.08 (< 0.01)	1.59	4.51	5.4 (0.1)
Three years after shelterwood cutting (S3)													
Oi								16	44.63 (1.62)	0.86 (0.03)			
0–5	13	0.59 (0.04)	0.78	9	66.6	19.1	14.3	20	6.58 (0.38)	0.31 (0.02)	0.09	14.64	5.6 (0.1)
5–10	13	0.78 (0.02)	0.71	8	73.9	20.5	5.6	19	2.03 (0.11)	0.10 (0.01)	0.63	5.55	5.3 (0.2)
10–30	13	0.80 (0.04)	0.70	8	73.0	22.3	4.7	20	1.84 (0.09)	0.09 (< 0.01)	0.66	2.82	5.6 (0.2)
30–50	9	0.79 (0.03)	0.70	6	69.0	26.1	4.9	19	1.52 (0.10)	0.09 (< 0.01)	0.77	3.34	5.7 (0.1)
Eight years after shelterwood cutting (S8)													
Oi								18	48.68 (0.87)	0.91 (0.04)			
0–5	11	0.49 (0.05)	0.81	9	58.5	23.4	18.1	17	11.14 (1.31)	0.52 (0.05)	0.05	17.34	5.6 (0.1)
5–10	11	0.76 (0.05)	0.71	9	71.7	22.1	6.2	18	2.45 (0.23)	0.13 (0.01)	0.42	10.05	5.2 (0.1)
10–30	10	0.83 (0.04)	0.69	9	67.9	26.6	5.5	19	1.98 (0.11)	0.10 (0.01)	1.91	5.82	5.4 (0.1)
30–50	5	0.91 (0.03)	0.66	9	63.8	29.8	6.4	17	1.57 (0.10)	0.09 (< 0.01)	2.07	7.82	5.4 (0.1)
Fourteen years after shelterwood cutting (S14)													
Oi								8	46.54 (1.23)	0.80 (0.03)			
0–5	20	0.51 (0.03)	0.81	8	54.0	25.4	20.6	18	11.36 (0.91)	0.58 (0.05)	0.03	25.81	5.7 (0.1)
5–10	17	0.83 (0.03)	0.69	8	71.4	22.8	5.8	19	3.99 (0.43)	0.22 (0.03)	0.02	15.24	5.7 (0.1)
10–30	17	0.92 (0.03)	0.65	8	69.4	23.9	6.7	20	2.15 (0.12)	0.10 (0.01)	0.80	6.21	5.6 (0.1)
30–50	13	0.91 (0.04)	0.66	8	65.1	26.9	8.0	20	1.98 (0.20)	0.09 (0.01)	2.13	6.48	5.5 (0.1)
Twenty-five years after an exploitative intervention (E25)													
Oi								20	46.11 (0.55)	0.93 (0.03)			
0–5	18	0.45 (0.06)	0.83	10	59.1	23.1	17.8	18	8.82 (0.62)	0.47 (0.03)	0.07	15.19	5.4 (0.1)
5–10	18	0.76 (0.04)	0.71	10	67.1	25.6	7.3	17	3.33 (0.27)	0.20 (0.02)	0.15	6.16	5.5 (0.2)
10–30	16	0.80 (0.03)	0.70	9	63.3	30.4	6.3	20	2.35 (0.12)	0.13 (0.01)	1.25	3.32	4.7 (0.1)
30–50	16	0.94 (0.04)	0.65	8	59.9	29.9	10.2	20	0.81 (0.12)	0.10 (0.01)	2.02	3.77	4.5 (0.1)

Values in parentheses indicate the standard error of the mean.
[a] Measured by sedimentation.
[b] Soil bulk density.
[c] Soil porosity calculated as $1-(\rho_b/\rho_s)$, where ρ_s is assumed as $2.65\,g\,cm^{-3}$.

(Table 2). Only the E25 stand soils showed a significantly lower percentage of sand in comparison to both the NI and S3 stands ($p = 0.006$). E25 also had a significantly higher percentage of silt in comparison to soils in both the NI ($p = 0.002$) and S3 ($p = 0.003$) stands. No significant differences were found in the clay fraction between the stands. In all the forest stands, clay content was significantly greater in the top 5-cm depth than in deeper soil layers.

No significant differences ($p < 0.05$) in soil bulk density were found. Soil bulk density increased with soil depth to a maximum value of 0.94 $g\ cm^{-3}$ (Table 2). The low soil bulk density and corresponding high porosity suggest a non-restrictive flow of water and air within the soil profile. Consistent with Bartsch and Rapp (1994) findings for sandy-loamy soils in the Lenga forests of northern Patagonia, the variation of pH with soil depth did not follow a distinct pattern (Table 2). Maximum decreases of pH in depth were only found in E25. In this case, historical extraction of trees may have changed the soil water balance – and thereby part of the biogeochemical cycle – increasing the acidity at lower depths. Generally, the soils in the study area can be classified as acid to strongly acid and are comparable to the pH values observed by Weber (2001) and Bava (1997) in soils of the Tierra del Fuego Lenga forests (3.0 to 4.6 and 3.0 to 3.9 respectively). These soils also show a horizon sequence typical of podzolization processes: an A horizon rich in SOC followed by a coarse textured E eluviation horizon. The E horizon was found between 5 and 15 cm depth (color: 10 YR5/3 to 2.5 Y 5/3).

The CEC_e followed a typical soil depth gradient in all of the forest stands, with lower values at deeper soil depths (Table 2). A small increase of CEC_e was found between the 10–30 and 30–50 cm soil depth intervals, which can be explained by increases in both clay content and, particularly, exchangeable Al. The CEC_e in the study area was lower than the values reported by Moretto et al. (2005) for Lenga forests in Tierra del Fuego (i.e. $21.6-28.2\,cmol_c\,kg^{-1}$).

3.2. Soil organic carbon

Despite the cold climate of the area and an expected slow biological degradation, the organic Oi layer was particularly thin (i.e. 1.6–3.5 cm thickness), with the lowest values occurring in the S3 stand. The total dry weights (TDW) of the Oi layers were not significantly correlated with actual tree density variables (i.e. number of trees per ha, basal area). The lowest accumulation of litter (4.91 $Mg\,ha^{-1}$) was found under the forest stand subjected to historical exploitation (E25). At the other forest stands, litter accumulation was 7.16 $Mg\,ha^{-1}$ (NI), 6.08 $Mg\,ha^{-1}$ (S3), 8.98 $Mg\,ha^{-1}$ (S8) and 7.58 $Mg\,ha^{-1}$ (S14).

Although significant differences in TDW were only detected between the NI and the S3 stand, it appears that shelterwood cutting caused an initial decrease in TDW, subsequently counteracted by the development of forest regeneration (see S8 and S14 regeneration values in Fig. 2). Caldentey et al. (2001) observed that 4 years after a shelterwood intervention in Lenga forests, litterfall decreased from 2.0 to 1.0 $Mg\,ha^{-1}$. It is hypothesized that after the initial decrease in litter inputs caused by shelterwood cuttings, the contribution of forest regeneration to the overall litterfall process increases, in turn causing TDW to rise again over the short term.

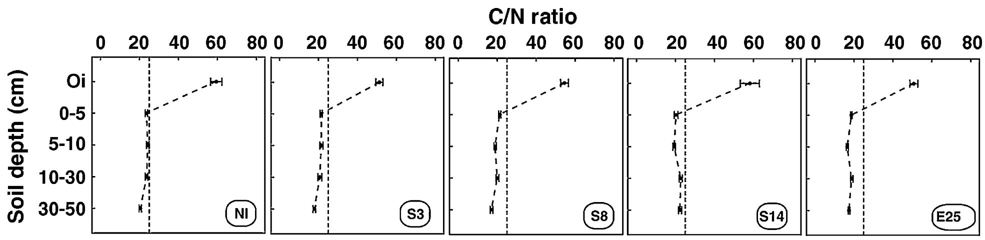

Fig. 3. C/N ratio at the different forest stands. Bars indicate the standard error of the mean. Dotted lines correspond to C/N = 25.

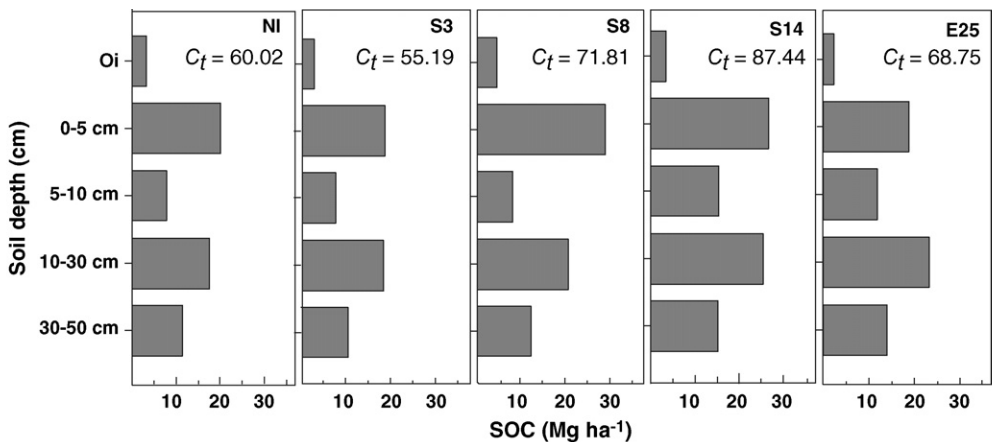

Fig. 4. Soil organic C at the different forest stands. The number in each graph indicates the sum of C_{total} for the entire soil profile. Sampling number was 40 for the Oi layers and 20 for the mineral soil layers.

This forest regeneration also creates more canopy cover which can decrease both soil temperature and soil water content, thereby retarding litter decomposition.

Organic Oe and Oa layers were not observed in any of the sampled forest stands. This is consistent with the studies of Bava (1997) and Weber (2001) who found little development of more decomposed organic layers in the Lenga forests of Tierra del Fuego. Although we found relatively high C/N ratios in the Oi layer (51–59), the C/N ratio decreased to values $<$ 25 in all sampled soil depths (Fig. 3). This indicates a rapid mineralization process, likely enhanced by the predominance of the sand fraction in all of the sampled soils. Coarse textured soils allow good aeration and infiltration conditions that facilitate the movement and redistribution of the products of the mineralization/humification process.

The total carbon content (C_{total}) of the Oi layer varied between 48.7 and 44.6% (Table 2). Similar results were found by Frangi et al. (1997) in Lenga forests of Tierra del Fuego. For the Oi layer, no significant differences in C_{total} were observed between the forest stands. However, SOC (expressed in a fractional basis) significantly decreased with soil depth ($p < 0.05$) in all forest stands (Table 2).

Fig. 4 shows the variation in SOC (Mg ha^{-1}) between the different forest stands. Up to a depth of 50 cm, SOC can be characterized as low (NI, S3, S8, and E25 stands) to moderate (S14 stand). Weber (2001) detected, on the average, 64 Mg C ha^{-1}, to a soil depth of 30 cm; in our study, SOC varied between 45 and 73 Mg C ha^{-1}. Significant differences in C_{total} (weight to weight basis) between forest stands by depth level are presented in Table 3. In the top 5 cm of the mineral soil, the NI stand presented no significant differences in C_{total} from the S8 ($p = 0.651$), S14 ($p = 0.144$) and E25 ($p = 1.000$) stands. Only the S3 stand showed a significantly lower C_{total} ($p = 0.008$) compared to the NI stand. However, the high variability in SOC recorded for the S8 and S14 stands (Table 2), may preclude significant differences in SOC between these stands. The S8 and S14 stands were characterized by canopy gaps of contrasting structure (only some gaps contained Lenga regeneration). Although there were no significant differences in C_{total} between the NI, S8 and S14 stands, stand microclimate may account for the higher C contents in both the S8 and S14 stands. Established regeneration can act as a radiation shield that inhibits decomposition of SOC in the upper soil layers. Furthermore, stand regeneration can increase litter input over time. Between the 10–30 cm and 30–50 cm soil sampling depths, there were no significant differences in C_{total} between almost all the sampled forest stands (Table 3).

Soil carbon storage and distribution is influenced by soil texture, microclimate and topography (Post, 1982; Dilustro et al., 2005; Vande Walle et al., 2001). These factors can explain, in part, the differences in SOC distribution between the sampled forest stands and soil depths. Since soil particle distribution was similar between the sampled stands, the observed differences in SOC are primarily a function of soil depth. Fig. 5 shows a positive correlation between clay content and SOC levels. Increased clay content can enhance the formation of clay–humus complexes and higher clay contents are associated with smaller soil pores that

Table 3
Significant differences in C_{total} (wt. %)

Forest stands	Soil depth (cm)			
	0–5	5–10	10–30	30–50
Non-intervened forest stand (NI)	a	ad	a	a
Three years after shelterwood cutting (S3)	b	a	a	a
Eight years after shelterwood cutting (S8)	ab	ac	ab	a
Four years after final cutting (S14)	a	bc	ab	a
Twenty-five years after an irregular non-silvicultural intervention (E25)	ab	bcd	b	a

Different letters indicate significant differences ($p \leq 0.05$) between forest stands for the same soil depth.

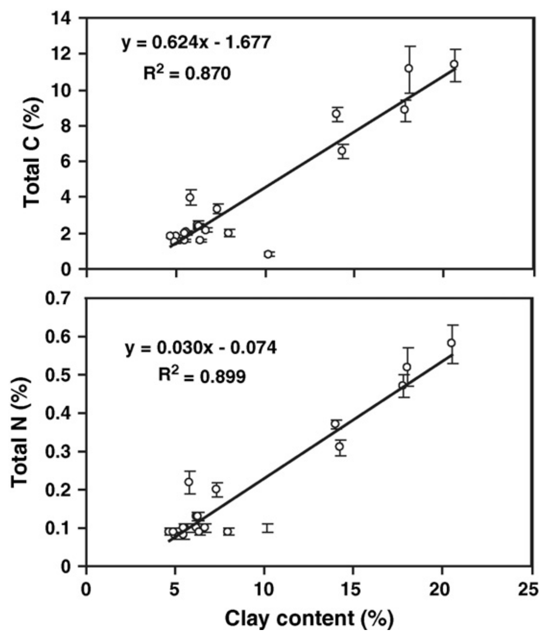

Fig. 5. Linear correlation between total soil C and total soil N with clay content. Data plotted correspond to the mean C and N content for each soil sampling depth at each forest stand. Bars indicate the standard error of the mean.

reduce the rate of organic matter oxidation by restricting soil aeration and soil water fluxes. Significant differences in SOC were only detected in the upper 10 cm of soil between the S3 stand and the remaining sampled stands, suggesting that forest interventions affect soil C storage at shallow soil depths over the short term. In the context of silvicultural applications, therefore, stand microclimate plays an important role in soil C storage. Caldentey et al. (2000) studied the short-term (4 years) effects of a shelterwood cut on the microclimate of Lenga forests in Magallanes, Chile. The global radiation in the intervened forest stand was four times greater than in a non-intervened forest stand. Furthermore, soil temperatures in the upper 30 cm of the mineral soil were higher in the intervened forest than in the non-intervened forest. Higher soil temperatures enhance biological activity and thereby the mineralization of soil organic matter and soil respiration (via roots and micro-organisms). Higher respiration activity increases the release of CO_2 to the atmosphere (Fischlin and Buchmann, 2004; Melillo et al., 2002) and consequently less SOC is stored in the organic layers and in the mineral soil. Both Peng and Thomas (2006) and Samuelson et al. (2004) have reported increased release of CO_2 from the soil to the atmosphere, caused by higher soil temperatures resulting from silvicultural interventions. Similarly Mormeneo et al. (2004) detected an increase in soil temperatures after silvicultural interventions in Lenga forest stands in Tierra del Fuego. In a subsequent study of the same forest stands Moretto et al. (2005) detected a decrease in SOC – within the same range as observed in our study – in the upper 10 cm of soil in the intervened stand. The effects of shelterwood cuts on SOC have been also described by Burschel and Huss (1997), who indicated a decrease in storage of organic material and consequently less SOC in the mineral soil to be the main effect of this type of intervention. Johnson et al. (2002) analyzed the SOC content of oak and pine stands in Tennessee, USA, without finding any long-lasting effects of harvesting treatments on SOC storage. Jiang et al. (2002) detected decreased soil C contents 10–20 years after harvesting of boreal larch forests in China, where SOC was reduced to pre-intervention levels once the litter inputs had been re-established.

4. Conclusions

Short-term effects of shelterwood cuts on SOC were only detected in the upper 10 cm of the mineral topsoil. A comparison of the SOC per area basis between the NI and S3 stands indicated a net loss of 5 Mg C ha^{-1}. Long-term effects of shelterwood cutting on SOC could not be verified for this type of forest. At deeper soil depths, SOC was not affected by either the silvicultural (shelterwood system) or exploitative interventions. The variation in SOC between the sampled forest stands can be explained by differences in soil texture, microclimate variation, and to some extent the initial decrease in litterfall caused by tree removal. The long-term storage of SOC in the soil profile is mostly affected by clay content. Lenga regeneration also seems to be a decisive factor in both microclimate variation and litter input to the soil. Therefore, in order to maintain the storage of SOC over time, silvicultural interventions in these type of forests require the development of Lenga regeneration. Shelterwood cutting could be scheduled and conducted in two separate intervention periods in order to mitigate the impact of interventions and minimize loss of SOC over the short term. Alternative silvicultural treatments, such as group selection felling, could also be utilized. However, for a better understanding of the effect of silvicultural treatments on SOC in the Lenga forests, more research on other C sources (such as root biomass, woody and non-woody debris) is needed.

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