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Trends in nutrient reservoirs stored in uppermost soil horizons of subantarctic forests differing in their structure

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Abstract Macro- (C, N, P, K, Ca and Mg) and micronutrient (Fe, Mn, Cu and Zn) reservoirs were estimated in the O (Oi+Oe+Oa) and in the A (0–10 cm depth) soil horizons of four stands of *Nothofagus pumilio* (lenga) from Tierra del Fuego which differ in their forestry characteristics. The type of soil layer (O and A) and the forest structure, as related to above-ground biomass storage, were assessed as a factor of variation in the nutrient reservoirs of both soils layers. Nutrient reservoirs showed similar ranges in both soil layers for total organic C (34–65 Mg ha^{-1}), total N (1.5–3.5 Mg ha^{-1}), rapidly available Ca (1.3–2.7 Mg ha^{-1}) and Mg (0.18–0.36 Mg ha^{-1}). Rapidly available K, available P, and medium-term available Fe and Cu were accumulated preferentially in A the horizons, whereas medium-term available Mn and Zn were mainly stored in the O horizons. The forest structure was not a statistically significant factor of variation on the nutrient reservoirs in the O horizons, although a legacy effect of the accumulated above-ground biomass on nutrient reservoirs in this soil layer can not be discarded. On the contrary, the pools of total organic C, total N, rapidly available K and medium-term available Cu and Zn in the A horizons varied significantly with the different forest structure. In terms of lenga forests sustainability, uppermost soils layers should be preserved as they accumulate most of the soil fertility which is essential for lenga regeneration after logging. The inclusion of the assessment of soil fertility in the management plans of the lenga forests in the ecotone of the Argentinean Tierra del Fuego is strongly recommended, as it will contribute to ensure a successful regeneration of lenga in logged areas.

Keywords *Nothofagus pumilio* · Forests · Soil · Surface horizons · Nutrient reservoirs · Tierra del Fuego

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Introduction

Lenga, *Nothofagus pumilio* (Poepp et Endl, Krasser), is the dominant deciduous tree species in the southernmost Andean-Patagonian forests and it posses a great forestry potential. Due to this, an intense logging pressure is threatening the sustainability of lenga forest in Argentinean Tierra del Fuego since last few decades.

Lenga forests management plans are mainly based in the structure of the forest stands defined by tree height, tree density, basal area, diameter at breast height, development stage, total over-bark volume and quadratic mean diameter between others (Vukasovic et al. 2004; Martínez-Pastur et al. 2009). The strategies to recover exploited areas are mostly restricted to the spontaneous natural lenga regeneration (Lencinas et al. 2007; Martínez-Pastur et al. 2007), while soils chemical characteristics are hardly considered in management plans and regeneration strategies in spite of logging affects to mineralization rate of organic matter and nutrient availability (Jurgensen et al. 1997; Prescott 2002) or even to the germination of lenga seeds and the growth of young trees (Yoshida et al. 2005).

Uppermost layers of lenga forests soils, comprising O horizons and the upper section of mineral A horizons, have crucial ecological functions in the preservation of the fertility of lenga forests soils. Thus, they are considered the main route for the return of lenga nutrients to soil (Frangi et al. 2005), its organic matter content contribute to the maintenance of soil moisture which is a major parameter for lenga regeneration (Martínez-Pastur et al. 2007), and they behave as a true reservoir of nutrients being indicative of soil fertility (Romanyà et al. 2005). Even the relevance of these soil layers increases as consequence of the relatively shallow rooting system of lenga trees.

The fertility of lenga forests soils probably results from a balance between organic matter mineralization and plant debris supplied by trees, which ultimately depended on the above-ground biomass used to define the structure of forest stands before logging was initiated. Thus, it is hypothesized that forest structure has a legacy effect on the soil fertility in logged areas that could affect afterwards to lenga regeneration.

To asses this hypothesis, soil reservoirs of macro- and micronutrients (as indicative of soil fertility) in lenga stands differing in above-ground biomass, i.e. forest structure, were estimated before logging in separate O horizons and upper centimetres of the mineral A horizons. Implications of the results in the improvement of management plans of lenga forests in Tierra del Fuego were also considered.

Materials and methods

Study area and soil sampling

The study was carried out in the lenga forests of Estancia Los Cerros which is located in the ecotonal zone of the Argentinean Tierra del Fuego (more details in S1, Appendix supplementary material for more). In this area, four lenga stands showing similar topography, soil parent material and climatic characteristics but, differing in their forest structure, were selected for this study. Differences in forest structure were associated to forestry parameters related to its above-ground biomass such as basal area, tree density and total over-bark volume (see S2 and Table A1 in Appendix supplementary material for more details). So, a decreasing pattern of accumulated above-ground biomass from the S1 stand (greater biomass storage) to the S4 stand (minor biomass storage) was defined. Taken into consideration that the main way of nutrient restore in lenga soils is the fall of senescent plant residues, it is hypothesized that the greater is the above-ground biomass the greater is the expected amount of plant debris that reach the uppermost soil layers contributing to a higher soil fertility. Thus, the fertility of lenga forest soils could be partially due a legacy effect of the forest structure, having potential implications in the future regeneration of lenga in logged areas.

Soil sampling was carried out in the four lenga stands (S1, S2, S3 and S4) where five representative locations were selected. In each location, samples of the entire organic horizon (2–12 cm depth depending on site) were collected using a hand shovel whereas to collect the uppermost 10 cm of the mineral soil (mostly A horizon) a soil corer was used. All soil samples were stored in plastic bags and transported to the laboratory where they were air-dried. Before the analytical determinations, samples from O horizons were sieved (4 mm mesh) and milled to 1 mm size whereas mineral soil samples were sieved using a 2 mm mesh.

Analytical determinations and soil nutrient reservoirs

The pH of the organic (O) and the mineral (A) soil samples was measured in water (pH_w) and 0.1 M KCl (pH_k) using a soil:solution ratio 1:2.5. Total contents of C and N were determined by a soil analyzer using finely-milled samples in an agate mortar. Three replicates of undisturbed 28.6 cm^3 cylinders were inserted in each soil layer (corresponding to O and uppermost A horizons) at every soil sampling location. Once in the laboratory, soil filled cylinders were oven-dried at 105 °C for 48 h and the soil weight obtained was use to calculate soil bulk density.

The particle-size distribution (sand: 2–0.05 mm; silt: 0.05–0.002 mm; clay: <0.002 mm) was determined in the A horizon samples by wet sieving (sand fraction) and using the international pipette method for silt and clay fractions.

Effective cation exchange capacity (eCEC), indicative of the degree of potential fertility of soil, was estimated as the sum of exchangeable base cations (Na_x, K_x, Ca_x and Mg_x) displaced with 1 M NH_4Cl and Al displaced by 1 M KCl. Values of exchangeable Ca, Mg and K were used to calculate the rapidly available pools of these macronutrients. Plant available phosphorous (extracted with a 0.03 M NH_4F plus 0.1 M HCl solution), and medium-term available Fe, Mn, Zn and Cu, i.e. micronutrients extacted with Na_2-EDTA, were also determined. For further details of the analytical procedures see S3 in Appendix Supplementary material. The concentration of all cations (Na, K, Ca, Mg, Al, Fe, Mn, Cu and Zn) was determined by flame atomic absorption (or emission) spectrometry, whereas P in Bray extracts was determined by visible spectrometry at 882 nm.

Soil nutrient reservoirs of total C and N, the pools of available P (P_{br}), rapidly available K, Ca and Mg (K_x, Ca_x and Mg_x) and medium-term available micronutrients (Fe_{dt}, Mn_{dt}, Cu_{dt}, Zn_{dt}), were calculated for both analyzed soil layers using the soil bulk density, horizon thickness and the concentrations of macro- and micronutrients, being expressed in mass unit (Mg or kg) per unit area (ha^{-1}).

Statistical analysis

The distribution of the data was tested for normality by the Kolmogorov–Smirnov (K–S), being log-transformed those parameters that not followed a normal distribution. Pearson correlations were applied to examine the existence of relationships between different soil nutrients, whereas a Stundent′s *t* test was used to detect significant differences in macro- and micronutrient reservoirs between organic (O) and mineral horizons (A). One-way analysis of variance (ANOVA) was used to test for differences in the soil nutrient reservoirs, as an estimate of soil fertility, using the forest structure as a classification factor. This considers that forest structure has a legacy effect on soil fertility through the storage of nutrients in the above-ground biomass that, finally, will reach soil surface through litterfall. All these analyses were carried out with SPSS v 17.0, being $P < 0.05$ used to indicate statistical significance.

Results

Physico-chemical characterization of soil layers

Particle-size distribution in the uppermost mineral soils (hereafter called A horizons) was dominated by the silt fraction (36–40 %; Table 1), leading to soil textures that varied from loam (S1 and S4 stands) to clay loam (S2 and S3 stands). As expected, soil bulk density was significantly lower in the O horizons (range 0.28–0.48 kg dm^{-3}) than in the A horizons (range 0.63–0.87 kg dm^{-3}).

Following the pH values (both in water and KCl solution), A horizons were slightly more acidic than O horizons (Table 1), whereas total organic C reached up to 295 g kg^{-1} in the organic horizons but did not surpass 75 g kg^{-1} in A horizons. Similarly, O horizons showed a higher total N content (6.6–11.4 g kg^{-1}) than A horizons (4.4 g kg^{-1}). Available phosphorous (P_{br}) is over 200 mg kg^{-1} in the organic horizons of all studied stands, a value that never was achieved in A horizons (Table 1). The concentrations of total C, total N and available P were significantly higher in O horizons than in A horizons as is shown in Table 1.

The eCEC, an estimate of the short-term soil fertility since it integrates rapidly available nutrients, was also significantly higher in O horizons (47–58 $cmol_c$ kg^{-1}) than in A horizons (14–24 $cmol_c$ kg^{-1}). However, both soil layers share the same sequence of abundance of exchangeable base cations: $Ca_x \gg Mg_x > K_x$ (Table 2), although the exchangeable acidity (percentage of saturation of the cation exchange complex by Al, SAl) was only

Table 1 Mean values (±standard deviation) for some soil parameters according to soil horizon and the structure of the forest stand

Stand	Hor[1]	*n*	Depth (cm)	B. D.[2] (kg dm^{-3})	Sand %	Silt	Clay	pH$_w$	pH$_k$	C g kg^{-1}	N	P$_{br}$ mg kg^{-1}
S1	O	5	4.2 ± 2.4	0.39 ± 0.07	n.d.	n.d.	n.d.	5.7 ± 0.6^a	4.8 ± 0.7^a	295 ± 124^a	11.4 ± 3.4^a	237 ± 111^a
	A	5	10	0.79 ± 0.03	21.6	40.4	38.0	5.2 ± 0.5^b	4.2 ± 0.7^b	75 ± 24^b	4.4 ± 1.2^b	192 ± 96^b
S2	O	5	8.2 ± 1.9	0.33 ± 0.04	n.d.	n.d.	n.d.	6.1 ± 0.2^a	5.3 ± 0.2^a	184 ± 55^a	6.6 ± 1.3^a	290 ± 67^a
	A	5	10	0.68 ± 0.05	39.3	39.1	21.6	5.3 ± 0.4^b	4.5 ± 0.5^b	50 ± 16^b	2.6 ± 1.1^b	126 ± 31^b
S3	O	5	10.0 ± 1.4	0.28 ± 0.04	n.d.	n.d.	n.d.	5.7 ± 0.3^a	4.9 ± 0.3^a	212 ± 112^a	8.8 ± 3.2^a	214 ± 87^a
	A	5	10	0.63 ± 0.10	27.7	36.1	36.3	5.0 ± 0.6^b	4.2 ± 0.6^b	65 ± 6^b	3.8 ± 0.1^b	161 ± 61^b
S4	O	5	4.8 ± 1.8	0.48 ± 0.06	n.d.	n.d.	n.d.	6.2 ± 0.2^a	5.4 ± 0.2^a	170 ± 16^a	7.7 ± 1.0^a	404 ± 69^a
	A	5	10	0.87 ± 0.12	31.8	39.1	21.6	5.7 ± 0.3^b	4.5 ± 0.4^b	64 ± 12^b	3.6 ± 0.8^b	154 ± 44^b

Means followed by the same letter are not significantly different ($P < 0.05$; student′s *t* test) between horizon type

[1] Soil horizon: organic (O) and uppermost 10 cm of mineral soil (A)

[2] Soil bulk density

relevant in A horizons where it reached up to 35 % in the plot S1 (Table 2).

The concentrations of medium-term available nutrients follow the sequence $Fe_{dt} \gg Mn_{dt} \gg Zn_{dt} > Cu_{dt}$, being significantly higher in the O horizons than in the A horizons unless for Fe_{dt}. The highest values of Fe_{dt} achieved almost 1,000 mg kg^{-1} in some O horizons (plots S1, S3 and S4), whereas mean values of Mn_{dt} were about 4.7 times more in O horizons than in A horizons (Table 2). The O horizons of S1 and S3 stands showed the highest values of Cu_{dt} (3–4 mg kg^{-1}) and Zn_{dt} (41–45 mg kg^{-1}), whose mean values for A horizons were 2 and 4 mg kg^{-1}, respectively (Table 2).

Macro- and micronutrients reservoirs in forests stands: influence of the nature of soil layer and the forest structure

The reservoirs of total C and N, available P and rapidly available Ca, Mg and K in the analyzed soil layers are shown in Table 3. More in detail, total C and N pools showed similar ranges for O and A horizons being 34–65 and 1.5–3.5 Mg ha^{-1} respectively. On the contrary, storage of available P (P_{br}) was significantly higher in the A horizons (0.15 Mg ha^{-1}) than in the O horizons (0.09 Mg ha^{-1}; Table 3).

Regarding the storage of rapidly available nutrients, the pools of Ca_x and Mg_x were relatively similar in both analyzed soil layers ranging from 1.3 to 2.7 Mg ha^{-1} for the former and from 0.18–0.36 to 0.18–0.34 Mg ha^{-1} for the latter. However, A horizons accumulated a significant higher amount of rapidly available K than the organic horizons especially in stands S1 and S4 (Table 3).

The reservoirs of medium-term available micronutrients followed the sequence $Fe_{dt} > Mn_{dt} \gg Zn_{dt} > Cu_{dt}$ in both soil layers (O and A horizons), although some differences were observed in the storage of Fe_{dt}, Zn_{dt} and Cu_{dt} between soil layers (Fig. 1). Thus, Fe_{dt} was significantly accumulated in the A horizons (mean 0.59 Mg ha^{-1}) compared to O horizons (0.22 Mg ha^{-1}), a trend that was also observed for Cu_{dt} pools (1.33 kg ha^{-1} in A horizons and 0.75 kg ha^{-1} in O horizons). In contrast, the pool of Zn_{dt} in the O horizons almost triplicate the value obtained in A horizons (2.8 kg ha^{-1}). Finally, no influence of soil layer was found for Mn_{dt} pools (Fig. 1).

Table 2 Mean values (±standard deviation) for concentrations of rapidly available nutrients, effective cation exchange capacity and Al saturation, and medium-term available nutrients according to soil horizon and the structure of the forest stand

Stand	Hor*	*n*	Ca_x $cmol_c\ kg^{-1}$	Mg_x	K_x	eCEC	SAl %	Fe_{dt} $mg\ kg^{-1}$	Mn_{dt}	Cu_{dt}	Zn_{dt}
S1	O	5	44 ± 13^a	10 ± 3^a	1.8 ± 0.8^a	58 ± 15^a	5 ± 2	1007 ± 138^a	460 ± 210^a	3.8 ± 0.7^a	45.2 ± 28.3^a
	A	5	16 ± 11^b	4 ± 2^b	1.1 ± 05^b	24 ± 10^b	35 ± 30	321 ± 903^a	92 ± 79^b	2.1 ± 0.5^b	5.8 ± 3.5^b
S2	O	5	35 ± 4^a	9 ± 2^a	1.7 ± 0.5^a	47 ± 5^a	–	769 ± 117^a	627 ± 240^a	2.8 ± 0.3^a	22.9 ± 10.8^a
	A	5	10 ± 5^b	2 ± 1^b	0.8 ± 0.4^b	14 ± 6^b	11 ± 11	693 ± 100^a	129 ± 59^b	1.5 ± 0.3^b	2.5 ± 0.8^b
S3	O	5	40 ± 13^a	10 ± 3^a	1.7 ± 0.3^a	52 ± 16^a	–	917 ± 177^a	346 ± 121^a	3.3 ± 0.8^a	41.5 ± 28.3^a
	A	5	13 ± 8^b	3 ± 1^b	0.7 ± 0.3^b	20 ± 7^b	16 ± 17	904 ± 256^a	79 ± 56^b	1.9 ± 0.4^b	3.9 ± 1.0^b
S4	O	5	44 ± 4^a	10 ± 1^a	2.3 ± 1.0^a	58 ± 5^a	–	941 ± 173^a	546 ± 81^a	2.8 ± 0.3^a	23.6 ± 4.1^a
	A	5	15 ± 7^b	3 ± 1^b	1.1 ± 0.3^b	20 ± 8^b	4 ± 3	644 ± 158^a	115 ± 21^b	1.6 ± 0.2^b	2.6 ± 0.8^b

x and dt subscripts refers to rapidly available nutrients (displaced with NH_4Cl) and medium-term available nutrients (extracted with Na_2-EDTA), respectively

Means followed by the same letter are not significantly different ($P < 0.05$; student's *t* test) between horizon type

* Soil horizon: organic (O) and uppermost 10 cm of mineral soil (A)

Results from the ANOVA test showed that the forest structure of the stand, whose classification is based on several parameters closely related to the accumulated above-ground biomass, was not a statistically significant factor of variation for the amount of nutrients stored in the O horizons. However, O horizon samples of stand S3 showed slightly higher reservoirs of total C and N, rapidly available nutrients (Ca_x, Mg_x and K_x) and some micronutrients (Fe_{dt}, Cu_{dt} and Zn_{dt}) than the O horizons of the other analyzed stands (Table 3; Fig. 1). For samples of A horizons, the lowest values of the pools of C, N, rapidly available Mg and some micronutrients (Cu and Zn) were observed in plot S2 (Table 3; Fig. 1), whereas the largest reserves of these nutrients in the A horizon were found in plots S4 (for C) and S1 (for N, Mg, Cu and Zn). Contrary to what happens in O horizons, it could be a legacy effect on soil fertility of uppermost mineral soil layers as some macro- and micronutrient pools were significantly influenced by the forest structure such as total organic C ($F = 4.77$, $P = 0.021$), total N ($F = 6.17$, $P = 0.008$), rapidly available K ($F = 4.30$, $P = 0.021$) and medium-term available Cu and Zn ($F = 6.27$, $P = 0.005$ and $F = 3.55$, $P = 0.038$, respectively).

Discussion

Physico-chemical characterization of soil layers

Soil parent material and the accumulation of organic matter are the main responsible of the texture in A horizons and bulk density in O horizons, respectively. The acidity in the analyzed soils is comparable to that reported for lenga forest soils in southernmost South America (Caldentey et al. 2001; Decker and Boerner 2003; Romanyà et al. 2005; Klein et al. 2008). Organic matter accumulation determines the differences in the total contents of C and N, available P and eCEC between O and A horizons, although their values are in the range of those published elsewhere (Gerding and Thiers 2002; Frangi et al. 2005; Romanyà et al. 2005; Klein et al. 2008). The saturation of the cationic exchange complex by base cations in O and A horizons confirm their role as reservoirs of rapidly available Ca, Mg and K as was indicated by Romanyà et al. (2005). The sequence of abundance of rapidly available base cations follows the chemical composition of leaves and

Table 3 Mean values (±standard deviation) for pools of C, N, available P and rapidly available nutrients according to soil horizon and the structure of the forest stand

Stand	Hor*	*n*	Res-C Mg ha^{-1}	Res-N	Res-P_{br}	Res-Ca_x	Res-Mg_x	Res-K_x
S1	O	5	37 ± 17^{a}	1.5 ± 0.5^{a}	0.04 ± 0.03^{a}	1.3 ± 0.6^{a}	0.20 ± 0.11^{a}	0.12 ± 0.10^{a}
	A	5	59 ± 18^{aAB}	3.5 ± 0.9^{aA}	0.15 ± 0.08^{bA}	2.5 ± 1.7^{aA}	0.34 ± 0.18^{aA}	0.33 ± 0.16^{bAB}
S2	O	5	50 ± 22^{a}	1.8 ± 0.6^{a}	0.08 ± 0.03^{a}	1.9 ± 0.5^{a}	0.30 ± 0.09^{a}	0.18 ± 0.06^{a}
	A	5	34 ± 12^{aA}	1.8 ± 0.8^{aB}	0.09 ± 0.03^{bA}	1.3 ± 0.7^{aA}	0.18 ± 0.08^{aA}	0.22 ± 0.11^{bAB}
S3	O	5	65 ± 33^{a}	2.7 ± 1.1^{a}	0.07 ± 0.03^{a}	2.5 ± 1.1^{a}	0.36 ± 0.13^{a}	0.21 ± 0.06^{a}
	A	5	37 ± 6^{aAB}	2.2 ± 0.1^{aAB}	0.10 ± 0.03^{bA}	1.5 ± 0.8^{aA}	0.23 ± 0.08^{aA}	0.16 ± 0.07^{bA}
S4	O	5	38 ± 19^{a}	1.7 ± 0.9^{a}	0.09 ± 0.05^{a}	2.0 ± 0.9^{a}	0.29 ± 0.13^{aA}	0.19 ± 0.08^{a}
	A	5	61 ± 12^{aB}	3.4 ± 0.7^{aA}	0.15 ± 0.05^{bA}	2.7 ± 1.2^{aA}	0.32 ± 0.11^{aA}	0.39 ± 0.10^{bB}

x subscripts refers to rapidly available nutrients (displaced with NH_4Cl)

Means followed by the same lower case letter are not significantly different ($P < 0.05$; student's *t* test) between horizon type, whereas different capital letter indicate significant differences in A horizons between stands showing distinctive forest structure ($P < 0.05$; ANOVA with Tukey-test)

* Soil horizon: organic (O) and uppermost 10 cm of mineral soil (A)

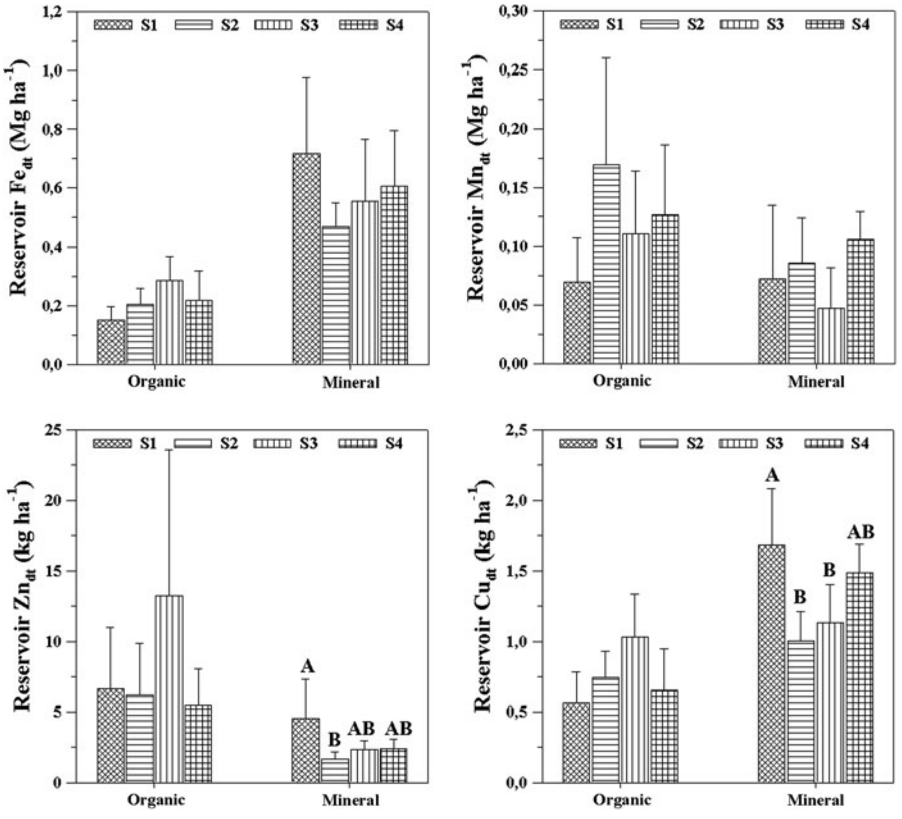

Fig. 1 Mean values and standard deviation of reservoirs of medium-term available nutrients (Fe_{dt}, Mn_{dt}, Zn_{dt} and Cu_{dt}) according to soil horizon and forest stand. *Different capital letter* indicate significant differences in A horizons between stands showing distinctive forest structure ($P < 0.05$; ANOVA with Tukey-test)

twigs in lenga litterfall, suggesting that plant residues are its main source in the analysed soil horizons. The predominance of Fe_{dt} among the medium-term available nutrients in A and O horizons agrees with Gerding and Thiers (2002), but contrast with Caldentey et al. (2001) who consider Mn_{dt} as the most abundant micronutrient in O horizons of lenga forest soils. The concentrations of Zn_{dt} and Cu_{dt} are lower than those from lenga forests soils in eastern Tierra del Fuego (Caldentey et al. 2001; Gerding and Thiers 2002), which could be attributed to a more intense recycling process in ecotone lenga forests.

Macro- and micronutrients reservoirs in forests stands: influence of the nature of soil layer and the forest structure

The reservoirs of total C, total N and available P in the O horizons exceeds that reported for these horizons in *N. pumilio* forests from southernmost South America (Caldentey et al. 2001; Frangi et al. 2005; Klein et al. 2008), being similar when referring to A horizons (Frangi et al. 2005; Peri et al. 2010). However, C stored in A horizons will strongly depend of its thickness as C concentration obtained at 20-30 cm of depth in soils from the study area varied from 9 to 51 g kg^{-1} (Nóvoa-Muñoz et al. 2008), whereas N accumulation results from its immobilization during the decomposition of lenga litter (Decker and Boerner 2006). Soil bulk density and the contribution of decaying roots would explain the similarity of C and N reservoirs in O and A horizons, whereas inorganic Al and Fe compounds could favour a greater P storage in the A horizons (Gerding and Thiers 2002). In any case, the levels of C, N and P stored in soil layers of studied lenga forests from the ecotone suggest that they behave as real nutrient reservoirs, preventing nutritional deficiencies for the regeneration and sustainability of lenga forests.

The pools of rapidly available nutrients follow the sequence $Ca_x \gg Mg_x \geq K_x$ in both O and A horizons coinciding with that reported by Frangi et al. (2005) and it is consistent with their abundance in leaves, twigs and bark of lenga which make up most of the senescent plant material from lenga trees, which finally reach the soil surface. The reservoirs of Mg_x and Ca_x in O horizons are significantly correlated with total C pools ($r = 0.595$, $P = 0.006$, $r = 0.579$, $P = 0.007$, respectively), being higher in the thicker O horizons (S2 and S3 stands; Table 3). On the other hand, the greater accumulation of K_x in A than in O horizons could result from the influence of the parent material during pedogenesis. The soil reservoirs of medium-term available nutrients (Fe_{dt}, Mn_{dt}, Cu_{dt} and Zn_{dt}) follow the sequence of abundance reported for lenga litterfall (Caldentey et al. 2001). Again litterfall is showed as the main source of these nutrients to O horizons, although the contribution of the weathering of the soil parent material to Fe_{dt} and Cu_{dt} pools in A horizons can not be excluded.

The absence of a significant statistical dependence between nutrient reservoirs of O horizons and forest structure does not necessarily imply the exclusion of a legacy effect of the above-ground biomass. Thus, a false homogeneity in nutrient reservoirs among plots with a contrasting above-ground biomass could be attributed to a large variation of C contents at short distances (Schulp et al. 2008), a high percentage of forest cover (Penne et al. 2010) or the heterogeneity of the thickness of the O horizons (Bens et al. 2006; Penne et al. 2010). In any case, our results depart from those obtained by Peri et al. (2010) who observed a greater C accumulation in soils as increase the above-ground biomass of *Nothofagus antarctica* forests.

On the contrary, forest structure was a significant factor of variation for the reservoirs of C, N, K_x, Cu_{dt} and Zn_{dt} in the uppermost section of the mineral soil (A horizons). This suggests the existence of a legacy effect of the above-ground biomass (forest structure) on soil fertility of the A horizons, but not as a straight relationship as could be expected. As consequence, the greater storage of nutrients in an A horizon does not correspond with the plot whose forest structure accumulate the greatest above-ground biomass. Similarly to our results, different studies already reported that tree development stage was responsible for the differences in C storage in forest soils (Grigal and Ohmann 1992; Scott et al. 2000; Davis et al. 2003), being attributed to the lower dynamism of the organic matter in A horizons compared to organic horizons (Davis et al. 2003). On the other hand, the limited depth of A horizons used for reservoir estimates (only the upper 10 cm) could constrain the influence of the forest structure (i.e. the above-ground biomass) in the amount of nutrients they stored as was suggested recently by Brandtberg et al. (2010).

Conclusions

Definitively, uppermost soil layers of lenga forests from the ecotone of the Argentinean Tierra del Fuego show a great ability to store nutrients. However, differences in the forest structure (i.e. in the above-ground biomass) seem to result in a legacy effect on the soil fertility influencing soil nutrient reservoirs, a fact that could affect a successful lenga regeneration in logged areas. Since the soil fertility of lenga forests could play a key role in their sustainability and natural regeneration, the conservation of the uppermost soil layers should be a priority task in the lenga forest management plans. Thus, during exploitation, it is strongly recommended the use of logging strategies that avoid the removal of the O horizons to minimize the risk of soil erosion. Simultaneously, this also ensures a favourable environment for a suitable mineralisation of organic matter which could guarantee the release of nutrients in accordance with the needs of forest regeneration. Other actions such as debarking of tree trunks, lopping felled trees or the maintenance of stumps and root systems of felled trees are also recommended to maintain the soil fertility. These guidelines should be included in the management plans of forests in the ecotone of the Argentinean Tierra del Fuego, but particularly in those forest stands characterized by low values of basal area, tree density and total over-bark volume. For these stands, it might think wrongly that they preserve nutrient reservoirs large enough to secure lenga regeneration after harvesting.

The total or partial disappearance of O horizons due to logging leads to a considerably reduction of soil fertility, conferring to A horizons a great significance as they are the only source of nutrients to ensure lenga regeneration. In this scenario, the quantification and preservation of the nutrient pools in A horizons should be also considered in the management plans of lenga forests, especially when it was observed a legacy effect of the structure of the forest masses in the fertility of soil where they grew.

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References

Bens O, Buczko U, Sieber S, Hüttl RF (2006) Spatial variability of O layer thickness and humus forms under different pine beech-forest transformation stages in NE Germany. J Plant Nutr Soil Sci 169:5–15

Brandtberg P-O, Davis MR, Clinton PW, Condron LM, Allen RB (2010) Forms of soil phosphorus affected by stand development of mountain beech (*Nothofagus*) forest in New Zealand. Geoderma 157:228–234

Caldentey J, Ibarra M, Hernández J (2001) Litter fluxes and descomposition in *Nothofagus pumilio* stands in the region of Magallanes, Chile. For Ecol Manag 148:145–157

Davis MR, Allen RB, Clinton PW (2003) Carbon storage along a stand development sequence in a New Zealand *Nothofagus* forest. For Ecol Manag 177:313–321

Decker KLM, Boerner REJ (2003) Elevation and vegetation influences on soil properties in Chilean *Nothofagus* forest. Rev Chil Hist Nat 76:371–381

Decker KLM, Boerner REJ (2006) Mass loss and nutrient release from decomposing evergreen and deciduous *Nothofagus* litters from the Chilean Andes. Austral Ecol 31: 1005–1015

Frangi JL, Barrera MD, Richter LL, Lugo AE (2005) Nutrient cycling in *Nothofagus pumilio* forest along an altitudinal gradient in Tierra del Fuego, Argentina. For Ecol Manag 217:80–90

Gerding V, Thiers O (2002) Caracterización de suelos bajo bosques de *Nothofagus betuloides* (Mirb) Blume, en Tierra del Fuego, Chile. Rev Chil Hist Nat 75:819–833

Grigal DF, Ohmann LF (1992) Carbon storage in upland forests of the Lake States. Soil Sci Soc Am J 56:935–943

Jurgensen MF, Harvey AE, Graham RT, Page-Dumroese DS, Tonn JR, Larsen MJ, Jain TB (1997) Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of Inland Northwest forests. Forest Sci 43: 234–251

Klein D, Fuentes JP, Schmidt A, Schmidt H, Schulte A (2008) Soil organic C as affected by silvicultural and exploitative interventions in *Nothofagus pumilio* forests of the Chilean Patagonia. For Ecol Manag 255:3549–3555

Lencinas MV, Martínez-Pastur G, Gallo E, Moretto A, Busso C, Peri PL (2007) Mitigation of biodiversity loss in *Nothofagus pumilio* managed forests of South Patagonia. In: Pacha MJ, Luque S, Galetto L, Iverson L (eds) Understanding biodiversity loss: an overview of forest fragmentation in South America. Part III: landscape ecology for conservation, management and restoration. International Association of Landscape Ecology, Wageningen, pp 112–120

Martínez-Pastur G, Lencinas MV, Peri PL, Moretto A, Cellini JM, Mormeneo I, Vukasovic R (2007) Harvesting adaptation to biodiversity conservation in sawmill industry: technology innovation and monitoring program. J Technol Manag Innov 2:58–70

Martínez-Pastur G, Cellini JM, Peri PL, Lencinas MV, Gallo E, Soler-Esteban R (2009) Timber management with variable retention in *Nothofagus pumilio* forests of Southern Patagonia. For Ecol Manag 258:436–443

Nóvoa-Muñoz JC, Pontevedra-Pombal X, Moretto A, Peña S, Escobar J, García-Rodeja Gayoso E (2008) Caracterización geoquímica de suelos forestales de lenga en el ecotono de Tierra del Fuego (Argentina). In: Barbosa OA (ed) Resúmenes del XXI Congreso Argentino de Ciencia del Suelo. Asociación Argentina de Ciencia del Suelo, Buenos Aires, pp 1–6

Penne C, Ahrends B, Deurer M, Böttcher J (2010) The impact of the canopy structure on the spatial variability in forest floor carbon stocks. Geoderma 158:282–297

Peri PL, Gargaglione V, Martínez-Pastur G, Lencinas MV (2010) Carbon accumulation along a stand development sequence of *Nothofagus antarctica* forest accros a gradient in site quality in Southern Patagonia. For Ecol Manag 260:229–237

Prescott CE (2002) The influence of the forest canopy on nutrient cycling. Tree Physiol 22:1193–1200

Romanyà J, Fons J, Sauras-Year T, Gutiérrez E, Vallejo V (2005) Soil-plant relationships and tree distribution in old growth *Nothofagus betuloides* and *Nothofagus pumilio* forests of Tierra del Fuego. Geoderma 124:69–180

Schulp CJE, Nabuurs GJ, Verburg PH, de Waal RW (2008) Effect of tree species on carbon stocks in forest floor and mineral soil and implication for soil carbon inventories. For Ecol and Manag 256:482–490

Scott NA, White JD, Townsend JA, Whitehead D, Leathwick JR, Hall GMJ, Marden M, Rogers GND, Watson AJ, Whaley PT (2000) Carbon and nitrogen distribution and accumulation in a New Zealand scrubland ecosystem. Can J For Res 30:1246–1255

Vukasovic, R., Martínez-Pastur G, Cellini JM (2004) Plan de manejo forestal "Los Cerros". Servicios forestales 13: 125–137

Yoshida T, Iga Y, Ozawa M, Noguchi M, Shibata H (2005) Factors influencing early vegetation establishment following soil scarification in a mixed forest in northern Japan. Can J For Res 35:175–188